ECONOMICS OF WHEAT YIELD VARIABILITY FOR OKLAHOMA FARMERS USING SATELLITE IMAGES

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TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table Page

CHAPTER I

CHAPTER II

CHAPTER III

CHAPTER III

CHAPTER IV

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

CHAPTER II

CHAPTER III

CHAPTER IV

Introduction

The first three chapters in this dissertation were presented as selected papers at the annual meetings of Southern Agricultural Economics Association, Western Agricultural Economics Association and American Agricultural Economics Association. The last chapter has been submitted to Journal of Agricultural and Applied Economics for publication.

CHAPTER I

Using Satellite Images for Precision Farming Decisions in Wheat Production

Introduction

In recent years, manufacturers of combines, control systems, yield monitors, and geographic positioning systems (GPS) have developed equipment to instantaneously measure and map grain yields while harvesting. Also, remotely sensed digital and photographic images have been used successfully to predict crop yields. For the most part, research and development of these technologies have been confined to higher value crops such as corn, soybeans, and cotton. Little work has been done on wheat and no substantive research has been conducted in Oklahoma. Until very recently, Oklahoma wheat producers have not used precision farming technology, both because they have not purchased new combines and because no research has indicated that these technologies will increase net returns. Although producers know that yields vary substantially within a field, they have not been able to locate, diagnose, and correct wheat yield deficiencies, or adjust inputs to match soil quality and pest infestations. Interpretation of satellite images appears to provide a low cost method of predicting wheat yield variability at the field level. If the underlying causes of yield variability can be identified and managed, the costs and returns of uniform versus site-specific management practices can be compared. Practices that reduce costs and/or increase yields and net returns can be identified for cooperating producers.

Previous Economic Research

In a review of literature on economic returns to site-specific management, Lowenberg-DeBoer and Swinton report that most published studies have been based on fertilizer response research. All of the studies they reviewed used partial budgeting analysis, but there was little consistency in the treatment of costs. Most studies included changes in the value of yield and the cost of nutrients required to achieve the yield (Beuerlein and Schmidt; Carr et al.; Fiez et al.; Hammond; Hayes et al.; Hertz and Hibbard; Reetz and Fixen; Wibawa et al.; Wollenhaupt and Buchholz; and Wollenhaupt and Wollowski). However, treatment of investment in equipment and information for site-specific management varied widely across the studies, and none included the costs of learning and training.

Among the more careful economic analyses reviewed, Hertz and Hibbard relied on custom rates for soil sampling and application costs (Lowenberg-DeBoer and Swinton). In the Wollenhaupt studies, costs of sampling, skilled labor, and site-specific management equipment were amortized over four years using straight-line depreciation. Studies that ignored the capital costs of site-specific information acquisition and management, as well as equipment use, may have seriously overestimated the potential profitability of site-specific management. Another economic deficiency in some studies was the absence of field information. Lowenberg-DeBoer and Swinton point out that an appropriate intermediate measure of profitability is the return to whole-field average fertilization. Soil test information is generally available and this return can be achieved without investment in site-specific management technology. Also, none of the studies reviewed examined the effect of site-specific management on temporal yield risk.

Lowenberg-DeBoer and Swinton also summarize the profitability results of 17 recent field crop studies of site-specific management. Overall, five studies found site-specific management profitable, six had results that were mixed or inconclusive, and six showed potential profitability (in the sense that site-specific management yielded higher net returns than whole-field management). Several factors accounted for a finding of profitability, including under-accounting of true costs, an assumed nitrogen response, and producing a high value crop. Several studies omitted the costs of site-specific sample collection and analysis, map making, and input application, while focusing on revenue gains. However, Schnitkey et al. and Malzer developed valid measures of potential profitability by calculating breakeven revenue figures needed to cover typical custom service costs ranging from $4 to $8 per acre.

In a recent economic analysis, Roberts, English and Mahajanashetti illustrate the potential benefits of variable rate nitrogen application and identify information needs. Lower costs, higher prices, and divergent yield response potentials were found to reduce the spatial variability required for profitable variable rate application. Information needs include sub-field yield response functions, prices, field spatial variability, and the cost of precision farming services. Also, Mahajanashetti, English, and Burton use a theoretical model to identify ranges of spatial variability required within multiple-land-class fields for economically viable variable rate technology (VRT) and the spatial variability required for maximum return to VRT. They illustrate that the return to VRT, and the viable range of spatial variability, increases for higher corn and nitrogen prices.

Few economic studies have used satellite remote sensing to predict crop yields at the field level, or to measure spatial and temporal yield variability. This study uses satellite remote sensing and sophisticated precision farming GIS software to produce maps that show wheat yields and yield variability at the field level for the period 1991 to 1998. The maps reveal considerable spatial variability for a given field and year, and considerable temporal yield variability for a given field from year to year. Some preliminary cost and return estimates are made to compare uniform versus site-specific applications of nitrogen fertilizer based on measures of spatial and temporal yield variability derived from satellite images.

Research Methods and Data

Satellite remote sensing is often used to obtain information on the physical characteristics of the earth's surface. Vegetation indices such as the Normalized Difference Vegetative Index (NDVI) have been used widely as an indirect measure of crop biomass and yield. The basis for the NDVI concept is the large spectral difference in the red and near infrared band reflectance of green vegetation (Itenfisu et al.). As the green biomass of the canopy increases, reflectance in the red band portion of the spectrum decreases due to absorbance for photosynthesis. At the same time, that in the near infrared band increases due to the internal structure of the leaves. The accumulated dry matter of a given crop at a given stage of growth is the result of the crop carbon dioxide intake, soil moisture uptake and net photosynthetic assimilation. Since NDVI is a measure of the photosynthetic activity of the vegetation, it is related to the crop potential yield and thus appears suitable for yield estimation.

To validate NDVI for this analysis, a single springtime Landsat Thematic Mapper (LTM) scene was acquired for north central Oklahoma for each of eight years during the

1990's. The dates of the selected scenes corresponded approximately to the heading stage of winter wheat in Oklahoma. The LTM data were converted to reflectance NDVI using established procedures. Multi-year yield data from university research plots were used to calibrate an exponential relationship between NDVI at the heading stage and final wheat grain yield. This relationship was independently tested using six years of yield data obtained from each of two farm cooperators with fields located near the calibration site. The performance of the prediction equation at these field sites was quite encouraging, especially considering that a single equation was used across years and that the crop's yield potential can change between the satellite overpass and harvest dates. A detailed discussion of the calibration and validation procedures is presented in Itenfisu et al.

For this economic analysis, an additional farm cooperator was identified in the area of north central Oklahoma covered by the satellite images. The cooperator identified a field and made available detailed records of input usage and wheat yields for the years for which we had satellite images. The field was then geo-referenced and located precisely on the satellite images. Sophisticated precision farming GIS software developed by SST Corporation was used to interpret the satellite images. The calibrated NDVI images were interpreted for the field and calibrated to the operator's actual yields. Then, a color map was prepared for each of several years for which a clear satellite image was available. Each map shows areas in the field for which wheat yields are predicted to be within specified bushel-per-acre ranges and indicates the average wheat yield per acre for that field and year.

Budgeting methods were used to compare the costs and returns associated with uniform applications of nitrogen across the field and site-specific applications of nitrogen. In analyzing uniform applications of nitrogen, the field is assumed to receive the quantity recommended by agronomists to produce a 50 bushel-per-acre yield goal and to achieve the average yield actually achieved in a given year. In analyzing site-specific applications, each micro-unit within the field is assumed to receive the pounds per acre recommended by agronomists to produce the average yield in that unit. For some areas of the field, the nitrogen application was greater than, and in other areas it was less than, that used in the analysis of uniform applications.

Results of the Analysis

The yield maps are an interesting initial result of the analysis. Figures 1, 2 and 3 show the yield maps derived from satellite data for the 139.6-acre field for the years 1999, 1997 and 1994. The average yields associated with the colors are shown below the yield maps and are different each year. The operator provided some additional information about the field. There are two basic soil types in the field. Approximately the left half of the field is a fine sandy loam soil and the right half of the field is a silt loam soil. However, both are Capability Class 1 soils. The red areas that show clearly on the 1999 yield map represent low areas in which drainage is a problem. These problem areas can also be seen on the 1997 and 1994 yield maps. Areas of low yields in the northwest and southeast areas of the field represent plow rows created during summer tillage operations.

The maps reveal substantial spatial yield variability during each of the three years. In 1999, estimated wheat yields (adjusted to measured average yield) varied across the field from a low of 19.5 bushels per acre to a high of 67.9 bushels per acre. For the eight yield ranges identified on the yield map, average yields varied from about 22.5 bushels per acre in the lowest yield range identified to 64.9 bushels per acre for the highest yield range (Table I). However, these low and high yield ranges represent a very small part (6.1 acres or 4.4 percent) of the field. The three yield ranges with average yields of 46.7, 52.7, and 58.8 bushels per acre represent about 79 percent of the 139-acre field. This point takes on additional significance when we discuss site-specific management of the field.

There is substantial temporal yield variability in this field, even though the operator indicated that nitrogen fertilizer was applied uniformly across the field each year. Average measured yields are considerably lower in 1997 and 1994, averaging 35.5 and 32.2 bushels per acre, respectively. Within the field, there was considerable spatial yield variability each year. In 1997, estimated yields averaged 14.5 and 46.6 bushels per acre in the lowest and highest yield ranges, while in 1994, yields averaged 23.8 and 40.4 bushels per acre in the lowest and highest yield ranges. Yield patterns within the field are somewhat similar from year to year. That is, high-yielding and low-yielding areas of a field were relatively consistent from year to year, even though the operator indicated that nitrogen fertilizer was applied uniformly across the field each year. Substantial spatial and temporal yield variability present analytical challenges for agricultural economists and managerial challenges for producers.

The operator provided detailed information regarding the machinery and equipment complement, tillage operations, seeding rates, fertilizer practices, use of insecticides and herbicides, and custom harvesting costs. Based on this information, detailed per acre cost and return budgets were developed for several scenarios using the OSU Enterprise Budget Generator.

The initial budgeting analysis focuses on estimating costs and returns for uniform applications of nitrogen across each field each year to achieve the operator's 50-bushel-per-acre yield goal. In 1999, this yield goal was achieved, but yields were substantially less than the goal in 1997 and 1994. As indicated in Table II, net returns above operating costs for 1999 are estimated to total $46.04 per acre. Under uniform applications of nitrogen to achieve a 50-bushel yield goal, net returns above operating costs total $27.14 in 1997 and $22.33 in 1994. When fixed costs are also considered, net returns above all costs are only positive in 1999.

One possible use of the satellite information is to allow producers to apply nitrogen fertilizer uniformly, but to fertilize for the yield actually achieved rather than for a 50-bushel-per-acre yield goal. Of course, the satellite information must be available before the top dress application of nitrogen in the spring. If the operator had this information, nitrogen use could possibly be reduced and net returns increased. In 1999, the operator actually achieved the 50-bushel-per-acre yield. Thus, net returns per acre are $46.04, are the same as estimated for the initial scenario. However, returns differ for 1997 and 1994 when average yields were 35.5 and 32.2 bushels per acre. Table III presents the cost and return budget for 1997 under the assumption that nitrogen is applied uniformly, but to achieve the yield actually achieved. Under this scenario, net returns above operating costs total $31.05 per acre in 1997 and $27.14 in 1994. So, if satellite information could be provided for, say, $3 per acre, net returns above operating costs could be increased in years of low yields due to reductions in nitrogen applications. In this case, the lower the average yield across the field, the greater the value of the satellite information.

The next scenario evaluates the possibility of site-specific management of nitrogen based on the yield maps derived from satellite information. Here, we assume that the field can be distinctly divided into micro-units based on the yield maps, and that the yields are uniform within each micro-unit. There are eight micro-units within the field each year, but the average yields within the micro-units are different each year. For example, in 1999, micro-unit one has an average yield of 22.5 bushels per acre and represents 2.2 acres (Table I). In 1997, micro-unit one has an average yield of 14.5 bushels per acre and represents 0.9 acres. In 1994, micro-unit one has an average yield of 23.8 bushels per acre and represents 2.9 acres. Under site-specific management, we assume that each micro-unit receives the amount of fertilizer required to produce the average yield within that unit. So, if a micro-unit has an average yield of 30 bushels per acre, that unit is assumed to receive the amount of nitrogen recommended by agronomic experts to produce a wheat yield of 30 bushels per acre. This same assumption is made for each micro-unit across the yield each of the three years included in the analysis. Table IV presents net returns per acre for 1994 under the assumption that nitrogen is applied under site-specific management at a cost of $3 per acre. The net returns above operating costs are $24.14 per acre, a figure that is $3 per acre less than uniform application to achieve the average yield achieved for the field that year. This result, which might be considered somewhat surprising, occurs because the nitrogen response function is linear, or nearly so, in the 30 to 50 bushel per acre ranges that produce most of the wheat across the field. Net returns above operating costs are $28.05 for 1997 and $42.82 for 1999.

Interestingly, it does not appear that site-specific management would be profitable in managing spatial variability within this field. Despite substantial differences in yields across the field each year, low yields and high yields are concentrated on relative few acres. Just three of eight micro-units represent 79 percent of the acres in 1999 and yields average 47, 53 and 59 bushels per acre in these units. In 1997, three micro-units represent 86 percent of the acres and yields average 33, 42, and 47 bushels per acre in these units. In 1994, four micro-units represent 81 percent of the acres and yields average 29, 31, 33, and 36 bushels per acre in these units. Reducing nitrogen applications on the low yielding acres does not save enough nitrogen to pay for the cost of site-specific applications.

It appears that satellite information could possibly be quite useful in managing temporal yield variability. The potential for nitrogen savings depends upon having the satellite information prior the top dress application of nitrogen in the spring. If the operator could learn that the potential yield was only 30 bushels per acre, rather than 50 bushels per acre, the top dress application could be reduced substantially, even if still applied uniformly.

Much research remains to be done. This analysis is based on one farm cooperator. We have two additional farmers and fields and intend to analyze each situation carefully. It is possible that other fields will be more variable and that site-specific management will have greater economic potential for managing spatial variability. A careful analysis of the sources of yield variability is needed for each field and across fields. Collection of data is under way for this component of the analysis. We have only just begun to study the combined risk associated with spatial and temporal yield variability. While our preliminary results suggest that temporal variability may offer greater potential for improved management, we remain optimistic, or at least hopeful, that something meaningful can be said about managing spatial variability.

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Table I:

YIELD MICRO-UNITS CALCULATED FROM SATELLITE DATA

Year	Micro-Unit	Acreage		Yield
		Value	Percentage	(bu/ac)
1999	Average			50.17
	1	2.20	1.6	22.50
	2	1.20	0.9	28.55
	3	5.50	3.9	34.60
	4	15.60	11.2	40.65
	5	32.70	23.4	46.70
	6	48.90	35.1	52.70
	7	29.50	21.1	58.75
	8	3.90	2.8	64.85
1997	Average			35.54
	1	0.90	0.6	14.50
	2	0.40	0.3	19.10
	3	3.20	2.3	23.70
	4	12.20	8.7	28.30
	5	39.60	28.4	32.90
	6	63.40	45.4	37.45
	7	18.30	13.1	42.00
	8	1.50	1.1	46.60
1994	Average			32.23
	1	2.90	2.1	23.80
	2	11.20	8.0	26.20
	3	22.00	15.7	28.55
	4	24.80	17.8	30.90
	5	37.20	26.6	33.30
	6	32.20	23.0	35.65
	7	8.90	6.4	38.00
	8	0.50	0.4	40.40

Table II:

WHEAT COST AND RETURNS (IN US $):

50 BUSHELS YIELD GOAL

	1999	1997	1994
OPERATING INPUTS			
WHEAT SEED	9.00	9.00	9.00
18-46-0 FERT	6.18	6.18	6.18
ANHYDROUS AMMON.	12.36	12.32	12.32
INSECTICIDE	-	-	-
CUSTOM HARVEST	12.00	12.00	12.00
CUSTOM HARVEST	3.62	1.86	1.47
CUSTOM HAULING	6.02	4.26	3.87
FERTSPREADER	2.25	2.25	2.25
GLEAN	-	-	-
ANNUAL OPERATING CAPITAL	2.86	2.86	2.86
MACHINERY LABOR	22.69	22.69	22.69
OTHER LABOR	2.60	2.60	2.60
MACHINERY FUEL, LUBE, REPAIRS	12.35	12.35	12.35
TOTAL OPERATING COSTS	91.92	88.36	87.57
FIXED COSTS			
MACHINERY			
DEPRECIATION	18.36	18.36	18.36
INTEREST	14.66	14.66	14.66
INSURANCE	0.98	0.98	0.98
TAX	2.55	2.55	2.55
TOTAL FIXED COSTS	36.54	36.54	36.54
PRODUCTION			
WHEAT	137.96	115.50	109.89
TOTAL RECEIPTS	137.96	115.50	109.89
RETURNS ABOVE TOTAL OPERATING COST	46.04	27.14	22.33
RETURNS ABOVE ALL SPECIFIED COSTS	9.50	(9.41)	(14.22)

Table III:

WHEAT COST AND RETURNS (IN US $):

ACTUAL YIELD AS YIELD GOAL

	1999	1997	1994
OPERATING INPUTS			
WHEAT SEED	9.00	9.00	9.00
18-46-0 FERT	6.18	6.18	6.18
ANHYDROUS AMMONIA	12.36	8.40	7.51
INSECTICIDE	-	-	-
CUSTOM HARVEST	12.00	12.00	12.00
CUSTOM HARVEST	3.62	1.86	1.47
CUSTOM HAULING	6.02	4.26	3.87
FERTSPREADER	2.25	2.25	2.25
GLEAN	-	-	-
ANNUAL OPERATING CAPITAL	2.86	2.86	2.86
MACHINERY LABOR	22.69	22.69	22.69
OTHER LABOR	2.60	2.60	2.60
MACHINERY FUEL, LUBE, REPAIRS	12.35	12.35	12.35
TOTAL OPERATING COSTS	91.92	84.45	82.75
FIXED COSTS			
MACHINERY			
DEPRECIATION	18.36	18.36	18.36
INTEREST	14.66	14.66	14.66
INSURANCE	0.98	0.98	0.98
TAX	2.55	2.55	2.55
TOTAL FIXED COSTS	36.54	36.54	36.54
PRODUCTION			
WHEAT	137.96	115.50	109.89
TOTAL RECEIPTS	137.96	115.50	109.89
RETURNS ABOVE TOTAL OPERATING COST	46.04	31.05	27.14
RETURNS ABOVE ALL SPECIFIED COSTS	9.50	(5.49)	(9.41)

Table IV:

WHEAT COST AND RETURNS (IN US $):

VARIABLE RATE APPLICATION

	1999	1997	1994
OPERATING INPUTS			
WHEAT SEED	9.00	9.00	9.00
18-46-0 FERT	6.18	6.18	6.18
ANHYDROUS AMMON.	12.59	8.40	7.51
INSECTICIDE	-	-	-
CUSTOM HARVEST	12.00	12.00	12.00
CUSTOM HARVEST	3.62	1.86	1.47
CUSTOM HAULING	6.02	4.26	3.87
FERTSPREADER	2.25	2.25	2.25
GLEAN	-	-	-
ANNUAL OPERATING CAPITAL	2.86	2.86	2.86
MACHINERY LABOR	22.69	22.69	22.69
OTHER LABOR	2.60	2.60	2.60
MACHINERY FUEL, LUBE, REPAIRS	12.35	12.35	12.35
VARIABLE RATE APPLICATION	3.00	3.00	3.00
TOTAL OPERATING COSTS	95.14	87.45	85.75
FIXED COSTS			
MACHINERY			
DEPRECIATION	18.36	18.36	18.36
INTEREST	14.66	14.66	14.66
INSURANCE	0.98	0.98	0.98
TAX	2.55	2.55	2.55
TOTAL FIXED COSTS	36.54	36.54	36.54
PRODUCTION			
WHEAT	137.96	115.50	109.89
TOTAL RECEIPTS	137.96	115.50	109.89
RETURNS ABOVE TOTAL OPERATING COST	42.82	28.05	24.14
RETURNS ABOVE ALL SPECIFIED COSTS	6.28	(8.49)	(12.40)

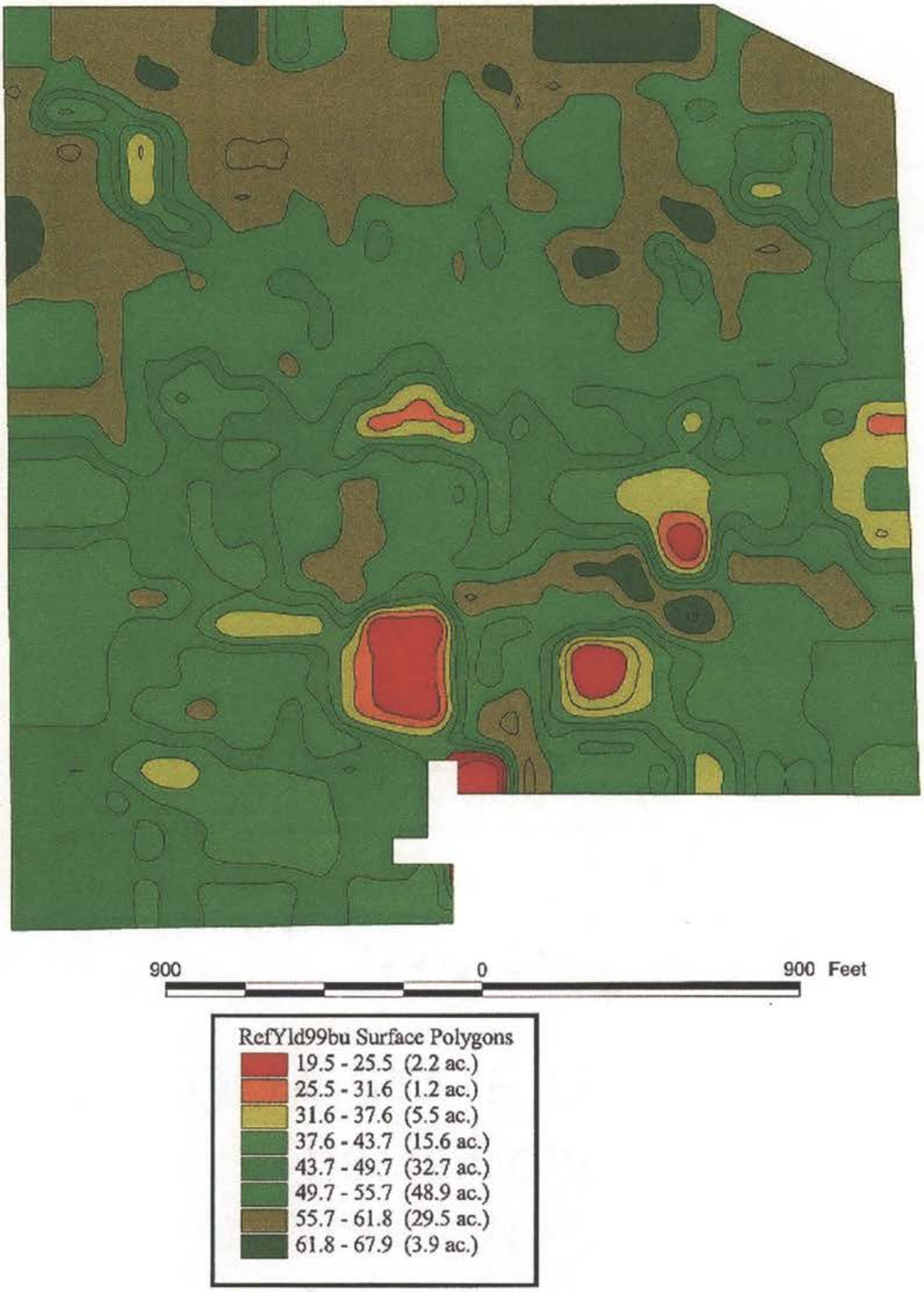


Figure 1: YIELD MAP FOR 1999

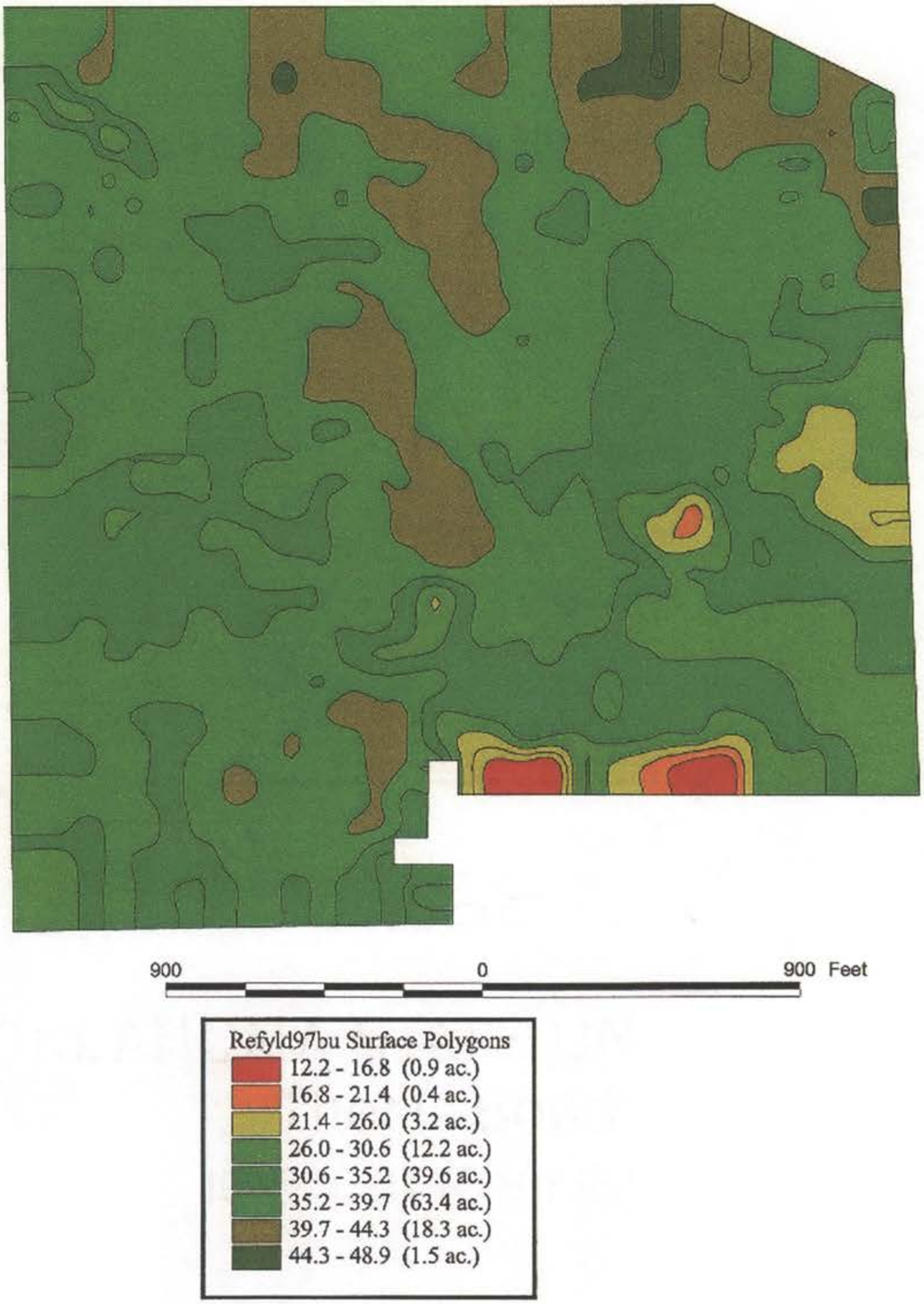


Figure 2: YIELD MAP FOR 1997

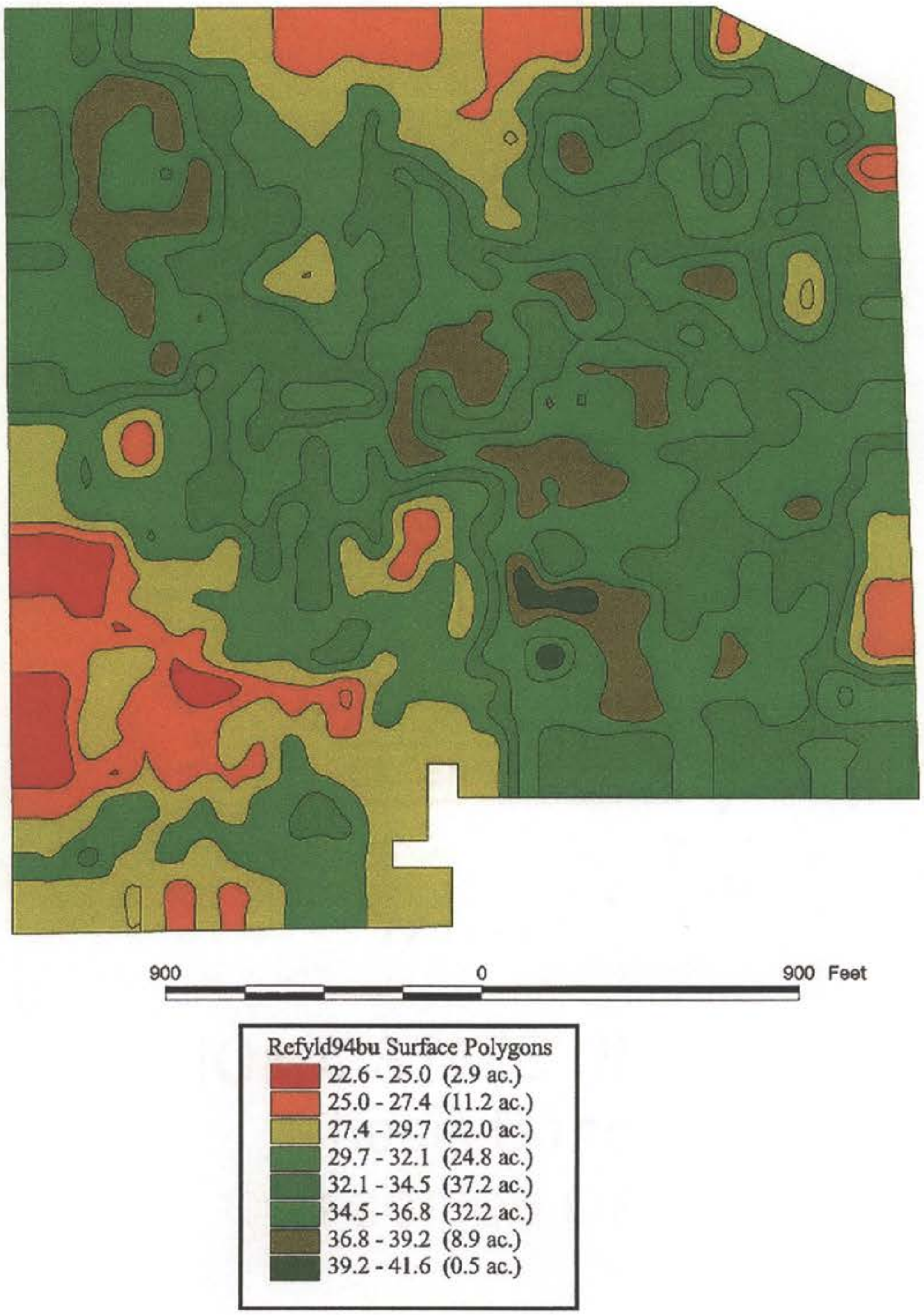
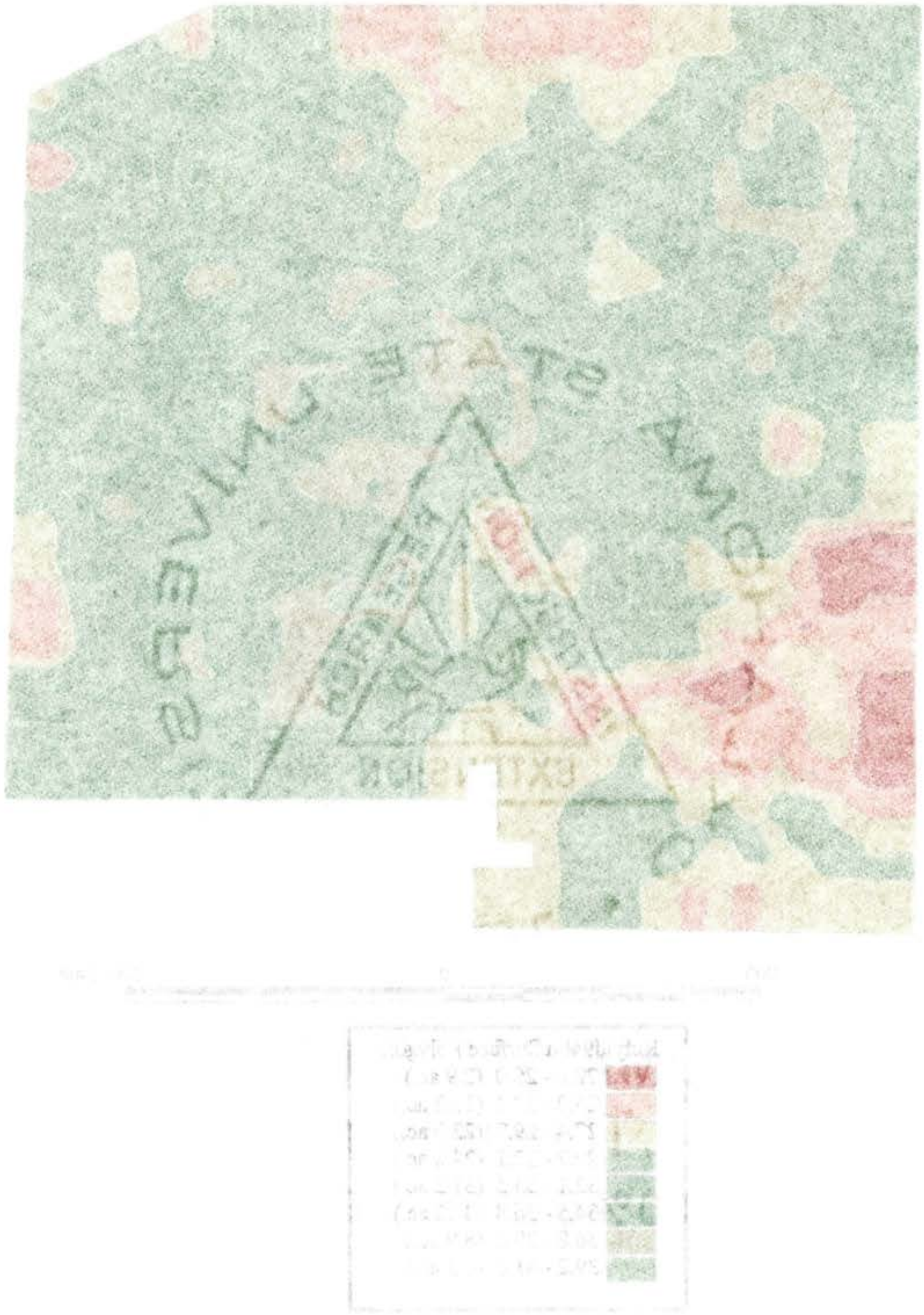


Figure 3: YIELD MAP FOR 1994



CHAPTER II

Using Remote Sensing to Analyze Spatial and Temporal Variability in Wheat Yields and Returns

Introduction

Wheat is one of the major crops grown in Oklahoma. As reported by Oklahoma Agricultural Statistics, 6.4 million acres of wheat were planted in 1998 and the value of production of winter wheat in 1999 was higher than any other Oklahoma crop. Wheat and products as a group generated approximately $162.8 million of export revenues in 1997, constituting 42% of the total export revenues from agricultural commodities.

Despite the importance of wheat in Oklahoma, its production is constrained by many biological and physical factors. Thus, wheat yields and net returns are quite variable from year to year and across the field in a given year. Traditional farm-level analysis assumes a uniform application of inputs across the field. However, recent technological developments with various degrees of sophistication have made it possible to analyze yield variability at the farm-level from both spatial and temporal perspective

Spatial farming technologies can be broadly classified into diagnostic and application categories. Global Positioning Systems, soil or pest sampling, and yield monitoring help in diagnosis of the problem. Examples of application technology include variable rate fertilizer applicators and seed planters.

Satellite imagery can be used to assess the extent of variability of yields across fields at a relatively low cost. The information can be obtained for past years for which farm level data may or may not be available. However, most precision farming research has focussed on the high value crops like corn and soybeans, with little work on wheat.

Previous Economic Research

In their review of seventeen precision farming studies, Lowenberg-DeBoer and Swinton note that all used partial budgeting analysis. Eleven of those studies focussed on corn. The only input managed was fertilizer and the costs were treated in an inconsistent fashion. Most studies included changes in the value of yield and the cost of nutrients required to achieve the yield (Beuerlein and Schmidt; Carr et al.; Fiez et al.; Hammond; Hayes et al.; Hertz and Hibbard; Reetz and Fixen; Wibawa et al.; Wollenhaupt and Buchholz; and Wollenhaupt and Wollowski). Lowenberg-DeBoer and Swinton noted the importance of identifying and including the appropriate cost components. Many studies overestimated the profitability by ignoring the capital cost of site-specific management while another underestimated the profitability by including non-essential costs. Another economic deficiency in some studies was the absence of field information. Lowenberg-DeBoer and Swinton point out that an appropriate intermediate measure of profitability is the return to whole-field average fertilization. Soil test information is generally available and this return can be achieved without investment in site-specific management technology. Also, none of the studies reviewed examined the effect of site-specific management on temporal yield risk.

Few economic studies have used satellite remote sensing to predict crop yields at the field level, or to measure spatial and temporal yield variability. This study uses satellite remote sensing and sophisticated precision farming GIS software to produce maps that show wheat yields and yield variability at the field level for the period 1991 to 1999. The maps reveal considerable spatial variability for a given field and year, and considerable temporal yield variability for a given field from year to year. Some preliminary cost and return estimates are made to compare uniform versus site-specific applications of nitrogen fertilizer based on measures of spatial and temporal yield variability derived from satellite images.

Research Methods and Data

Satellite remote sensing is often used to obtain information on the physical characteristics of the earth's surface. Vegetation indices such as the Normalized Difference Vegetative Index (NDVI) have been used widely as an indirect measure of crop biomass and yield. The basis for the NDVI concept is the large spectral difference in the red and near infrared band reflectance of green vegetation (Itenfisu et al.). Since NDVI is a measure of the photosynthetic activity of the vegetation, it is related to the crop potential yield and thus appears suitable for yield estimation. To validate NDVI for this analysis, a single springtime Landsat Thematic Mapper (LTM) scene was acquired for north central Oklahoma for each of eight years during the 1990's. The dates of the selected scenes corresponded approximately to the heading stage of winter wheat in Oklahoma. The LTM data were converted to reflectance NDVI using established procedures. Multi-year yield data from university research plots were used to calibrate an exponential relationship between NDVI at the heading stage and final wheat grain yield. This relationship was independently tested using six years of yield data obtained from the farm cooperators with fields located near the calibration site. The performance of the prediction equation at these field sites was quite encouraging, especially considering that a single equation was used across years and that the crop's yield potential can change between the satellite overpass and harvest dates.

Analysis and Results

Three farm cooperators were identified in the area of north central Oklahoma covered by the satellite images. The cooperators identified a field and made available detailed records of input usage and wheat yields for the years for which we had satellite images. The field was then geo-referenced and located precisely on the satellite images. Precision farming software developed by SST Corporation was used to interpret the satellite images. The calibrated NDVI images were interpreted for the field and calibrated to the operator's actual yields. Then, a color map was prepared for each of several years for which a clear satellite image was available.

The maps are composed of many small pixels, each representing approximately 0.1544 acre, so estimated yield information is shown for every one-sixth of an acre. Smaller pixels indicate better resolution of the image containing more information. Since each of the pixels is geo-referenced, with unique latitude and longitude coordinates, yield estimates for unique pixels can be calculated and compared for different years. One of the advantages of using satellite imagery is that yield estimates are obtained for years for which little field-level information is available. However, inclement weather conditions, like clouds at the time when the image is taken, can render it useless for this research.

The fields, identified as A, B, and C, are 157.3, 57.3 and 139.7 acres respectively. Each map shows areas in the field for which wheat yields are predicted to be within specified bushel-per-acre ranges and indicates the average wheat yield per acre for that field and year. The pixels on the border of each field have been excluded from the analysis because of their irregular size and a possible non-uniform treatment. Hence, the numbers of pixels included in the analysis are 963, 286 and 857 respectively. The three fields studied range from field A, which is relatively homogenous in terms of soil type and elevation, to field B, which has more physical variability with terraces and different soil types. Field C has two basic soil types, but is relatively level.

Eight years of estimated yield data are available for fields B and C. For the field A, however, information for one of the years could not be used due to cloudy conditions. For each of the three fields, pixel level statistics are given in tables I-III. For field A, the estimated pixel yield (adjusted to measured average yield) ranged from a minimum of 10.05 bu/ac (1996) to a maximum of 73.19 bu/acres (1999) over the past seven years. For field B, the pixel yield varied from 9.18 bu/ac (1996) to 65.12 (1994). In case of field C, a minimum of 12.22 bu/ac (1997) and a maximum of 70.18 bu/ac (1998) comprised the pixel yield range. Thus, for each of the fields the range of yields obtained across the field is very high. The annual average measured yields for the three fields also vary substantially over the period studied (from 24.67 bu/ac to 58.53 bu/ac for A, from 15.65 bu/ac to 50.15 bu/ac for B, and from 26.06 bu/ac to 58.14 bu/ac for C). The annual coefficient of variation ranges from 0.07 (1992) to 0.16 (1999) for field A, from 0.14 (1999) to 0.34 (1996) for field B, from 0.09 (1992, 1993) to 0.18 (1991) for field C. The coefficients of variation indicate that the data for the most part are relatively equally variable about the annual means. For field B particularly, higher coefficients of variation tend to be associated with lower average yield years.

To further analyze spatial yield variability, individual pixels were studied intensively. Using 1999 as the base year, the multiple-year yield data set for each of the fields was sorted from lowest- to highest-yielding pixels. Pixels were chosen from the sorted data sets using fixed intervals from the entire yield range. Yield estimates for the chosen pixels were ranked from the lowest to the highest across the years. Assuming that there is an equal chance of obtaining any of the yields, each of the estimates was assigned an equal probability of occurrence. Then, cumulative probability distribution functions were developed for each of the chosen pixels. The cumulative probability graphs for each of the fields reveals that for most of the pixels across field A, regardless of location, the probability of obtaining a yield of 30 bu/acre yield lies somewhere between 0.40 and 0.50. There is a similar probability of getting a yield of 25 bu/ acre for field B and a yield of 35 bu/acre for field C. Thus, almost all of the pixels in each field, even those with extremely low yield during the base year 1999, have almost a fifty percent probability of producing a level of output much higher than the one actually achieved in 1999.

The per acre average operating costs for uniform input applications are $88.78, $94.85 and $88.28 for the three fields. Cumulative probability distributions graphs for net returns (figure 1) reveal that the probability that field A will generate an income of less than or equal to breakeven (net of operating expenses) is between 0.5 and 0.7. For field B, similar probability is between 0.6 and 0.8, while for field C it is almost 0.5.

If we assume, as many previous studies have, that yield variability is caused by nitrogen deficiency, then uniform versus site-specific practices can be compared. Budgets have been developed for the fields to compare uniform application of nitrogen with variable rate management. Each of the fields is divided into eight micro-units based on estimated yields. For variable rate management, each of the micro-units is fertilized to achieve the average yield of that particular micro-unit, at an assumed cost of $3 per acre. The results indicate that the total fertilizer consumption increases when managed variably, leading to higher costs than for uniform nitrogen application. Hence, the variability across the field for a given year is not large enough to warrant the use of precision farming a cost of $3 per acre. This result is partly related to a nearly linear nitrogen response function in the range of application levels required. However, it should be noted that while field B is still being analyzed, spatial variability in fields A and C does not appear to be related to fertilizer deficiencies or other inputs identified in previous studies. Thus, managing spatial variability appears challenging and satellite images may not provide good managers with uniform soils much opportunity to increase returns through precision farming.

The annual average yields for the fields were used to develop the graphs for returns net of the operating costs (figure 2). The graphs indicate considerable fluctuation in average net revenue across years for all three fields. Thus, temporal variability may be of equal or greater importance than spatial variability from a management standpoint.

To further investigate this possibility, quantitative procedures were used to estimate the significance of variables representing time and space. A variable 'year' is used for years of data availability across the field. Another variable 'site' represents each of the pixels across years. The dependant variable, 'yield', contains the information regarding the yield in bu/acre for a particular pixel for a particular year. The 'year' variable includes the effect of variability due to meteorological factors while the 'site' variable includes the effect of variability due to site-specific factors. A simple means model was specified using the GLM procedure in SAS, describing Yield as a function of fixed Year and Site variables. Tables IV-VI summarize the result of the analysis. High R^2 values indicate that the dummy variables used account for most of the variability in yields across time and space. Both of the variables are significant, however the F-test value for time is much greater than that for the location variable. It appears that the year variable, representing temporal variability, is responsible for most of the variation in all the fields.

The overwhelming temporal variability may be further explained by including weather-related variables, like rainfall, in the model. Similarly, it would be helpful to include soil types and other physical characteristics of the fields to better explain the spatial variability. The evidence of high temporal variability emphasizes the importance of the time of availability of satellite imagery to the farm decision-maker. Resource-usage at the farm level could perhaps be optimized if the images were made available at a point when the management practices could be tailored according to the expected output. For example, an indication of lower than average yields due to weather-related events could lead the farmer to reduce spring fertilizer applications uniformly or in a site-specific pattern to reduce input costs and moderate the decline in net returns per acre.

Conclusions

Satellite imagery provides a great opportunity to access historical information for detailed quantitative and descriptive analysis of individual fields and farms. The cost of accessing the information is expected to decrease with the increased availability and improvement in technology. The promise of this technology is the greatest in fields with highly variable yields resulting from soil variations and manageable inputs. Such soils can perhaps be more efficiently managed through spatially variable technologies. However, the potential usefulness of site-specific management in less variable fields may not be economically viable. The technology could possibly be useful in managing temporal yield, and hence revenue, variability. The potential for fertilizer savings in wheat may depends upon having the satellite information prior to the top dress application of nitrogen in the spring. If operators could learn that the potential yield was less than original yield goal, they could reduce the top dress application substantially, even if still applied uniformly, to maintain net returns.

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Table I:

WHEAT YIELD STATISTICS: FIELD A

	Reference Yield (bushels/ Acre)						
	1999	1998	1996	1994	1993	1992	1991
Minimum	30.66	32.90	10.05	22.04	22.26	19.22	18.42
Maximum	73.19	72.64	34.16	58.86	69.92	30.71	38.21
Average	54.11	58.53	24.67	48.89	54.78	25.44	27.29
Standard Deviation	8.62	6.93	3.66	5.16	8.09	1.87	3.93
Coefficient of Variation	0.16	0.12	0.15	0.11	0.15	0.07	0.14

Table II:

WHEAT YIELD STATISTICS: FIELD B

	Reference Yield (bushels/ Acre)							
	1999	1998	1997	1996	1994	1993	1992	1991
Minimum	25.06	33.96	12.09	9.18	22.73	18.84	9.86	20.81
Maximum	64.81	61.99	53.75	43.62	65.12	49.16	29.53	58.98
Average	50.15	45.59	28.59	17.80	44.96	33.10	15.65	40.28
Standard Deviation	6.88	6.80	9.55	6.07	8.36	5.31	3.69	7.50
Coefficient of Variation	0.14	0.15	0.33	0.34	0.19	0.16	0.24	0.19

Table III:

WHEAT YIELD STATISTICS: FIELD C

	Reference Yield (bushels/ Acre)							
	1999	1998	1997	1996	1994	1993	1992	1991
Minimum	19.39	19.66	12.22	19.90	22.58	27.99	15.76	20.00
Maximum	67.45	70.18	48.75	45.12	41.42	68.41	32.54	55.91
Average	50.01	58.14	35.51	36.41	32.24	54.74	26.06	36.90
Standard Deviation	8.20	7.88	4.51	3.64	3.51	5.12	2.39	6.64
Coefficient of Variation	0.16	0.14	0.13	0.10	0.11	0.09	0.09	0.18

Table IV:

ANOVA TABLE: FIELD A

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	Pr>F
Year	6	1368556.375	228092.729	10100.0	<.0001
Site	962	107068.860	111.298	4.93	<.0001

R^2 = 0.918834 Coeff Var = 11.32568

TABLE V:

ANOVA TABLE: FIELD B

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	Pr>F
Year	7	337983.3812	48283.3402	1406.85	<.0001
Site	285	42551.6719	149.3041	4.35	<.0001

R^2 = 0.847510 Coeff Var = 16.97288

TABLE VI:

ANOVA TABLE: FIELD C

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	Pr>F
Year	7	798046.9792	114006.7113	4208.74	<.0001
Site	856	52761.0435	61.6367	2.28	<.0001

R^2 = 0.839790 Coeff Var = 5.204623

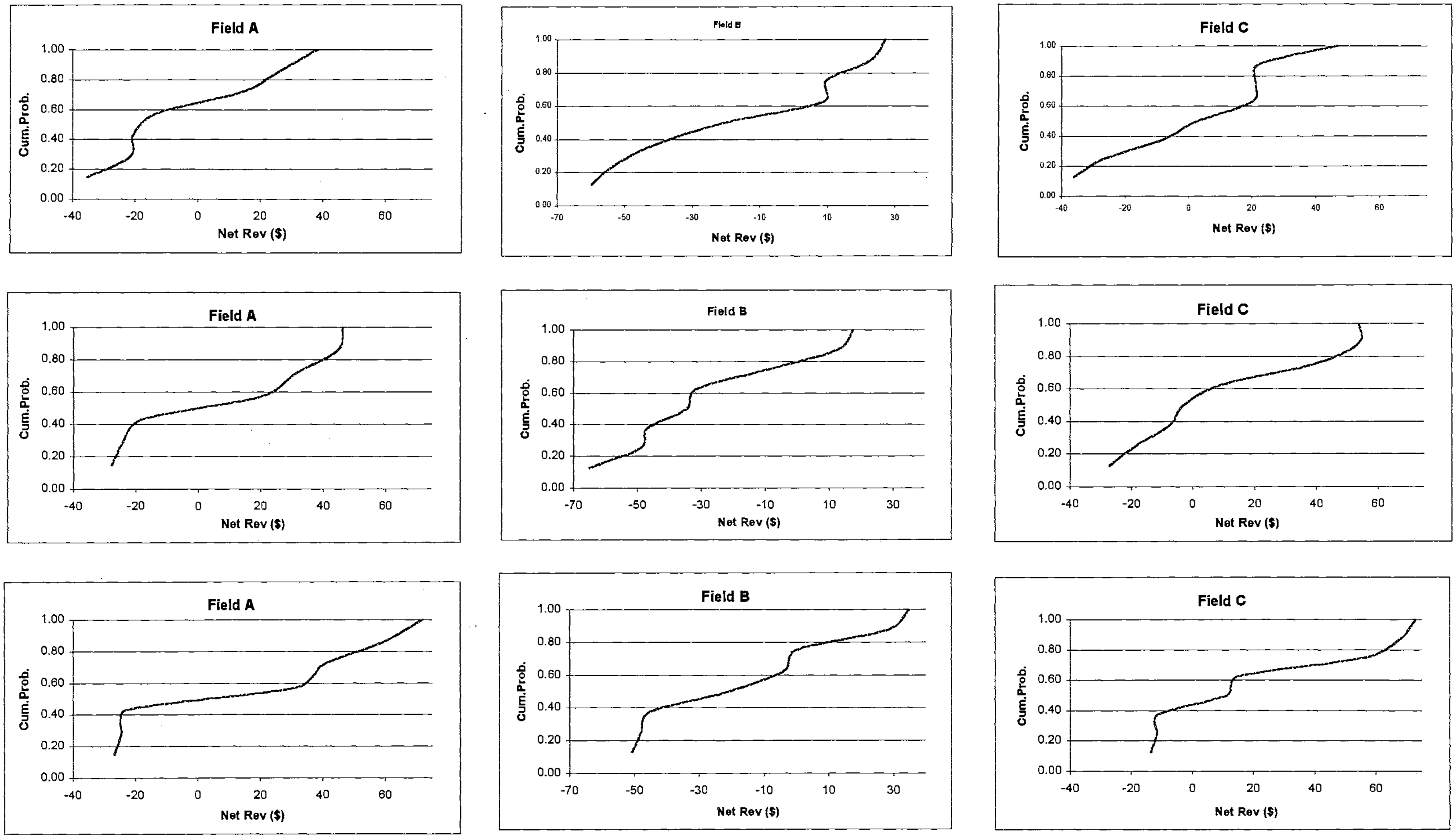

Figure 1: CUMULATIVE PROBABILITY GRAPHS FOR NET REVENUE:
Three Selected Pixels for each Field

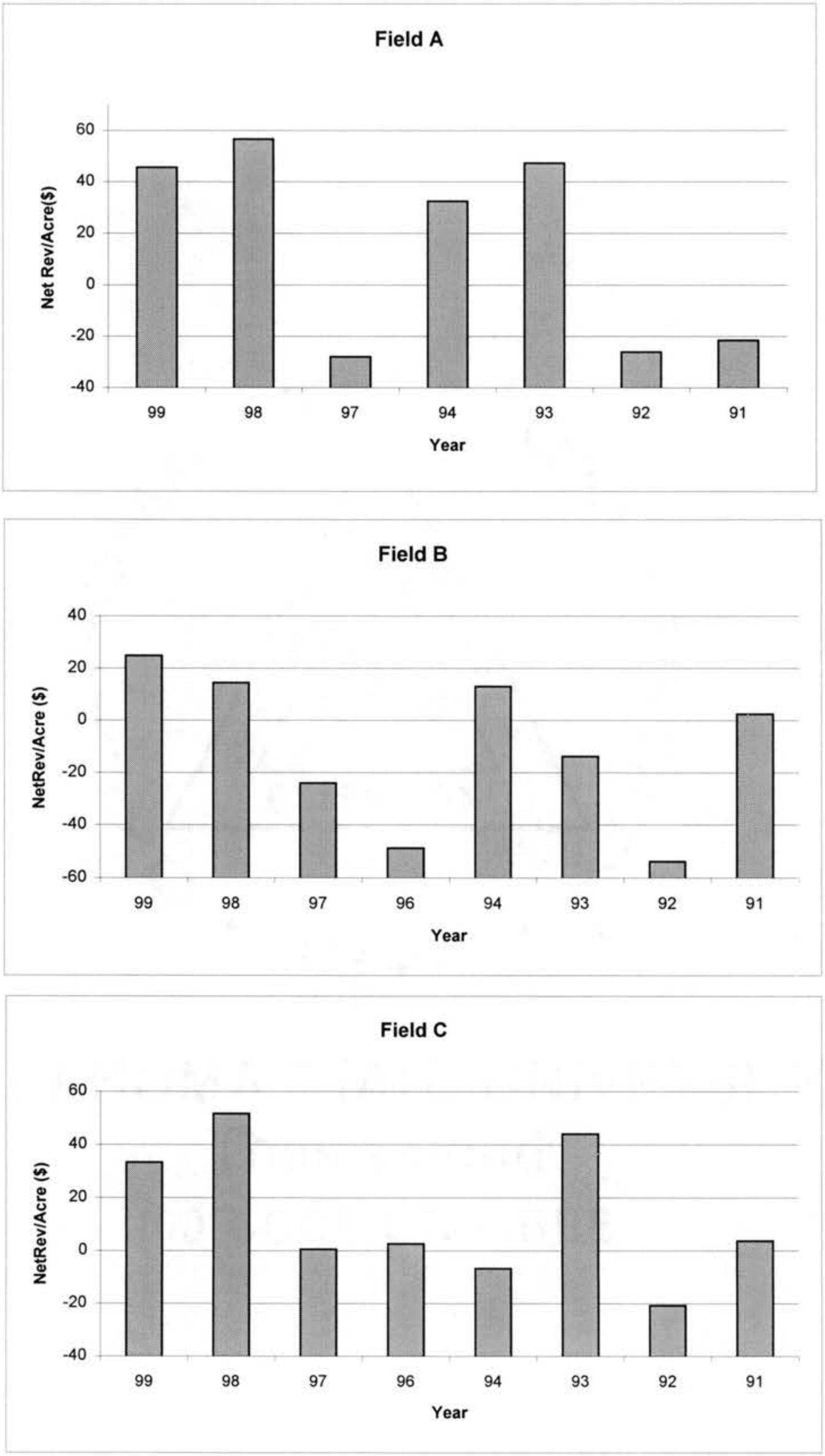

Figure 2: ANNUAL AVERAGE NET REVENUE PER ACRE

CHAPTER III

Using Spatial and Temporal Variability to Identify Site-Specific Management Areas in Wheat

Introduction

Wheat plays an important role in the agricultural economy of Oklahoma. It generates the highest value of production for any crop and is one of the major sources for export revenue. Due to its importance, the quest for improved methods of producing the crop is very important. Improved technologies can either help increase the revenues through increased production or reduction in costs through optimal and efficient allocation of inputs.

Precision farm management is a relatively new way of addressing the problem through optimal spatial allocation of inputs. The basic premise of the technology is that if different parts of a field yield significantly differently, they should not be treated based on the average yield goal for the whole field. The idea is to replace the conventional practice of uniform management of the fields with a more variable and site-specific management. The inputs can be seed, fertilizer, insecticide, drainage tile, subsoiling, or others. The variability can be differences in type of input or rate of application.

Precision farming can be practiced at various levels. The more sophisticated the technology, the higher the costs of applying it. While most of the spatial management research has focussed on high-value crops, low market value of wheat limits the number of economically feasible alternative technologies available.

First step in spatial management is diagnostic - getting to know one's field. It means the identification of the high and low producing parts of the field. The tools available include yield monitors, global positioning systems and satellite imagery. The costs of obtaining satellite images are going down as they become increasingly available and they might provide a cheaper alternative to the yield monitors.

Interpretation of satellite images appears to be a feasible method of assessing and predicting wheat yield variability at the field level. The information can be obtained for past years for which field level data may or may not be available. The next step would be an effort to explain the cause of variability, which may involve soil and pest sampling. This would help in identifying distinctly different zones of the field with different management requirements.

Once both the incidence and cause of yield variability have been diagnosed, application technologies like variable rate fertilizer applicators and seed planters can be used to provide the remedial solution.

Until very recently, Oklahoma wheat producers have not used precision farming technology, both because they have not purchased new combines and because no research has indicated that these technologies will increase net returns.

Previous Economic Research

High value crops have been the major focus of the research work related to site-specific management, and partial budgeting analysis is one of the most frequently used procedure in determining the economic feasibility of precision farming. In their review of seventeen precision farming studies, Lowenberg-DeBoer and Swinton note that all used partial budgeting analysis, while eleven of them studied corn. Fertilizer was the only input managed, and costs were treated in an inconsistent fashion. Most studies included changes in the value of yield and the cost of nutrients required to achieve the yield (Beuerlein and Schmidt; Carr et al.; Fiez et al.; Hammond; Hayes et al.; Hertz and Hibbard; Reetz and Fixen; Wibawa et al.; Wollenhaupt and Buchholz; and Wollenhaupt and Wollowski).

In their summary of the studies reviewed, Lowenberg-DeBoer and Swinton report that five studies found site-specific management profitable, six had results that were mixed or inconclusive, and six showed potential profitability (in the sense that site-specific management yielded higher net returns than whole-field management). However, under-accounting of true costs, an assumed nitrogen response, and producing a high value crop were some of the drawbacks of the profitability studies. Several studies omitted the costs of site-specific sample collection and analysis, map making, and input application, while focusing on revenue gains. Schnitkey et al. and Malzer developed valid measures of potential profitability by calculating breakeven revenue figures needed to cover typical custom service costs ranging from $4 to $8 per acre.

Swinton and Ahmed in their survey of farmers' profitability from investment in precision agriculture equipment found that yield monitors are the precision technology most widely purchased by farmers. High costs of some processes and equipment, like grid soil sampling and variable rate technology controllers, was a major source of concern among the farmers.

Few economic studies have used satellite remote sensing to predict crop yields at the field level, or to measure spatial and temporal yield variability. This study uses satellite remote sensing and sophisticated precision farming GIS software to produce maps that show wheat yields and yield variability at the field level for the period 1991 to

1999. The maps reveal considerable spatial variability for a given field and year, and considerable temporal yield variability for a given field from year to year. Some preliminary cost and return estimates are being made to compare uniform versus site-specific applications of nitrogen fertilizer based on measures of spatial and temporal yield variability derived from satellite images.

Research Methods and Data

Satellite remote sensing is often used to obtain information on the physical characteristics of the earth's surface. Vegetation indices such as the Normalized Difference Vegetative Index (NDVI) have been used widely as an indirect measure of crop biomass and yield. The basis for the NDVI concept is the large spectral difference in the red and near infrared band reflectance of green vegetation (Itenfisu et al.). As the green biomass of the canopy increases, reflectance in the red band portion of the spectrum decreases due to absorbance for photosynthesis. At the same time, that in the near infrared band increases due to the internal structure of the leaves. The accumulated dry matter of a given crop at a given stage of growth is the result of the crop carbon dioxide intake, soil moisture uptake and net photosynthetic assimilation. Since NDVI is a measure of the photosynthetic activity of the vegetation, it is related to the crop potential yield and thus appears suitable for yield estimation.

To validate NDVI for this analysis, a single springtime Landsat Thematic Mapper (LTM) scene was acquired for north central Oklahoma for each of eight years during the 1990's. The dates of the selected scenes corresponded approximately to the heading stage of winter wheat in Oklahoma. The LTM data were converted to reflectance NDVI using established procedures. Multi-year yield data from university research plots were used to calibrate an exponential relationship between NDVI at the heading stage and final wheat grain yield. This relationship was independently tested using six years of yield data obtained from each of two farm cooperators with fields located near the calibration site. The performance of the prediction equation at these field sites was quite encouraging, especially considering that a single equation was used across years and that the crop's yield potential can change between the satellite overpass and harvest dates. A detailed discussion of the calibration and validation procedures is presented in Itenfisu et al.

For this economic analysis, three farm cooperators were identified in the area of north central Oklahoma covered by the satellite images. The cooperators identified a field and made available detailed records of input usage and wheat yields for the years for which we had satellite images. The field was then geo-referenced and located precisely on the satellite images. Sophisticated precision farming GIS software developed by SST Corporation was used to interpret the satellite images. The calibrated NDVI images were interpreted for the field and calibrated to the operator's actual yields.

Then, a color map was prepared for each of several years for which a clear satellite image was available. Each map shows areas in the field for which wheat yields are predicted to be within specified bushel-per-acre ranges and indicates the average wheat yield per acre for that field and year.

Each map is composed of many small pixels. The size of pixel indicates the resolution of the image and the amount of information contained therein. Smaller pixels in most cases are preferred to large one. In our case, the size of a pixel is approximately

0.1544 acre. Hence we can get the estimated yield information for almost every one-sixth of an acre. Since each of the pixels is geo-referenced, with unique latitude and longitude coordinates, yield estimates for unique pixels can be calculated and compared for different years.

One of the advantages of using satellite imagery is that we can obtain yield estimates for years for which we do not have much field-level information. However, inclement weather conditions, like clouds, at the time when the image is taken can render it useless for our purpose. The operators provided detailed information regarding the machinery and equipment complement, tillage operations, seeding rates, fertilizer practices, use of insecticides and herbicides, and custom harvesting costs for budgeting analysis.

Results of the Analysis

The fields studied are of different sizes. These are 157.3, 57.3 and 139.7 acres respectively for the fields identified as A, B, and C. Yield maps for those fields contain 1098, 432 and 993 pixels respectively. However not all the pixels for all of the maps could be used for analysis. The pixels on the border of each field have been excluded from the analysis because of their irregular size and a possible non-uniform treatment. Hence, the numbers of pixels included in the analysis are 963, 286 and 857 respectively.

Eight years of estimated yield data is available for fields B and C. For the field A, however, information for one of the years could not be used due to cloudy conditions.

The three fields studied range from field A, which is relatively homogenous in terms of soil type and elevation, to field B, which has more physical variability with terraces and different soil types. Field C has two basic soil types, but is relatively level.

For any given year of data, the pixels are grouped into eight equally spaced yield ranges. For the eight yield ranges identified on the yield map, the average yields vary considerably from the minimum to the maximum. Acreage and yield information for three selected years for each of the fields is shown in table I. For example, yields range from 11.6 bu/ac to 32.7 bu/ac for field A in 1996. However, these low and high yield ranges represent a very small part (9.8 acres or 6.2 percent) of the field. The three yield ranges with average yields of 23.6, 27.1, and 30.1 bushels per acre represent about 77 percent of the field. This point takes on additional significance when we discuss site-specific management of the field.

For each of the three fields, annual yield range and averages are given in table II. For field A, the yield on individual pixels ranged from a minimum of 10.05 bu/ac (1996) to a maximum of 73.19 bu/acres (1999) over the course of past seven years. For the field B, the yield varied from 9.18 bu/ac (1996) to 65.12 (1994). In case of field C, a minimum of 12.22 bu/ac (1997) and a maximum of 70.18 bu/ac (1998) comprised the yield range. This shows that for each of the fields, the range of yields obtained from different parts of the fields is very high. The factors causing this variation are spatial for a given year and temporal across the years.

Yield variability based on the coefficient of variation is mapped in figures 1-2 for fields A and B. The maps classify each of the fields into four areas: very low variability (0-10 percent), low variability (10-20 percent), variable (20-30 percent) and high variability (greater than 30 percent). The 30 per cent cut-off point was chosen after consultation with the plant scientists. For field A, areas classified as slightly and highly represent only about 2.4 percent of the field and are concentrated in two small regions of the field. From a management standpoint, those areas could be treated differently. However, they only represent a total of 3.7 acres and site-specific management is probably not economic. For field B, areas classified as slightly and highly variable make up about 40 percent of the total area but they are scattered through out the field. Site-specific management in this case would probably require specialized and expensive equipment.

Annual average yield was used to normalized estimated yields for that year. The annual normalized yields were averaged across years. For a better understanding of the data, 'management zone' yield maps are developed (figures 3-4) for the two fields using the coefficient of variation and normalized averages for the pixel yield data across years. The resulting maps visually indicate the pattern of yield consistency in different parts of each field. The long-term averages have been used to classify parts of each field into four categories: areas with consistently high yields, consistently average yields, consistently low yields, and inconsistent yields. Consistently high yielding zone includes pixels with normalized yields greater than 105 per cent of the average normalized yields. Pixels with yields ranging between 95 -105 percent of the average normalized yield comprise the consistently average yielding zone. The consistently low yielding management zone includes pixels with normalized yield below 95 percent of the average normalized yield. Management zones are an important tool when using multiple-year information for a field as they summarize the spatial and temporal information available for a field over time.

For field A, it can be seen that the field can broadly classified into two zones. Almost 84.7 percent (133.3 acres) of the field has been consistently producing average or high yield, while 14.6 percent (23 acres) is categorized as the consistently low yield area. The low yield area is concentrated in the southeastern and southwestern part of the field. Only a very small portion of the field, 1.1 acres, has inconsistent yields. It corresponds with the high variability area in figure 1.

For field B, the definition of the zones is not as clear as for field A. The area with consistently average-and-above-average yield comprises 70.6 percent (40.5 acres) of the field, while 22.7 percent (13.0 acres) results in consistently low yields. The low yield areas are relatively scattered over a larger part of the field. Yields for 3.8 acres in field B are inconsistent. The inconsistent yield area was classified as the high variability area in figure 2.

The concept of defining management zones based on long-term normalized yield averages could help in decision making as it presents the variability visually. The size and location of zones with significantly different yield averages may be important in assessing the feasibility of variable rate farming systems. The cost of using alternative technologies is important for a low-value crop like wheat. The costs of site-specific management can be minimized if the distinct management zones are relative large in size. In such a case it may be feasible to tailor management practices based on the long term yield pattern. On the other hand, the presence of numerous, small management zones in the field may make necessary the use of more sophisticated machinery. The greater investment adds to the management costs and may make site-specific management economically infeasible.

From the analysis of management zones, areas of consistently high, average and low yields over a number of years can be determined for any given field. The fields under study were treated uniformly based on average yields. Assuming nitrogen as the only variable of choice we can conclude that, over the years, different parts of the field have been responding differently to the fertilizer applications. Hence, it is reasonable to assume the existence of a unique response function for each of those zones. Not enough information is yet available to draw those precise yield response functions.

We also assume that the response functions for different zones will have different intercepts, indicating different yield levels at no-fertilizer level, and different slopes. Each one of them arrives at a yield plateau but at different nitrogen levels. The low yielding zone, with poor soil, arriving at that level earlier and the high yielding zone, with good soil, taking the longest to reach that level. Uniform application of fertilizer at a given level will produce different yield depending on the type of soil. As shown in the figure 5, for uniform application of fertilizer based on the average yield goal, it is expected that the poor soil yield response will be somewhere in the flat region of the function, average soil yield response will be at a level closer to the flat region, while yield response for good soil will be pretty far from reaching that level.

For the identified management zones, costs and returns of uniform and variable management can be compared using budgeting procedures. The operators have provided detailed information regarding the machinery and equipment complement, tillage operations, seeding rates, fertilizer practices, use of insecticides and herbicides, and custom harvesting costs. Based on this information, detailed per acre cost and return budgets are being developed for several scenarios using the OSU Enterprise Budget

Generator. The idea is to manage each of the management zone keeping in view a zonal yield goal, long term yield average for that zone, rather than treating it on whole field average. Variable rate (zonal in this case) management will be economically feasible only if any savings in input application exceed the additional costs incurred.

The temporal variability is being studied by including weather-related variables, like rainfall, in the model. This effort is being conducted for field C. Similarly, it might be helpful to include soil types and other physical characteristics of the fields to better explain the spatial variability phenomenon. This effort is being conducted for field B.

Conclusions

Satellite imagery provides a great economic opportunity to study the spatial and temporal yield variability as it exists on the farmers' fields at low cost. The costs are expected to decrease as the technology advances and becomes more popular. Fields with highly variable yields resulting from soil variations and manageable inputs will gain the most from this technology. Such soils can perhaps be more efficiently managed through spatially variable technologies. However, its potential usage in less variable fields still needs further investigation. Perhaps excellent managers who are using annual soil tests to insure that fertilizer deficiencies do not exist should be told that site-specific management of inputs is probably not economic for these uniform fields. However, management zone maps can still serve as a helpful tool in identifying the parts of field with different management needs, particularly on less uniform fields. Size and location of the management zones play an important role in determining the feasibility of variable rate management. Larger management zones concentrated in fewer parts of the fields are more economical to manage variably than smaller zones scattered all across the field.

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Table I:

AVERAGE YIELD RANGES FROM YIELD MAPS

Year	Field A			Field B			Field C		
	Area		Yield	Area		Yield	Area		Yield
	Acres	%age	(bu/ac)	Acres	%age	(bu/ac)	Acres	%age	(bu/ac)
1996	1.3	0.8	11.6	3.6	6.3	10.1	0.8	0.6	21.5
	3.0	1.9	14.6	5.3	9.2	11.9	2.0	1.4	24.7
	6.8	4.3	17.6	7.9	13.8	13.6	2.7	1.9	27.9
	16.5	10.5	20.6	13.4	23.4	15.5	11.9	8.5	31.1
	34.3	21.8	23.6	16.5	28.8	18.4	37.4	26.8	34.2
	49.3	31.3	27.1	6.3	11.0	22.3	50.3	36.0	37.4
	37.7	24.0	30.1	1.3	2.3	27.5	29.7	21.3	40.5
	8.5	5.4	32.7	3.0	5.2	37.1	4.8	3.4	43.7
1998	1.2	0.8	35.4	3.1	5.4	33.1	0.4	0.3	22.9
	9.4	6.0	40.4	8.4	14.6	37.1	1.4	1.0	29.3
	24.3	15.4	45.3	9.2	16.0	40.6	3.1	2.2	35.7
	29.8	18.9	50.3	10.2	17.8	43.6	4.4	3.1	42.0
	27.9	17.7	55.3	8.6	15.0	46.5	14.4	10.2	48.4
	36.2	23.0	60.2	6.4	11.1	49.5	29.7	21.1	54.7
	23.2	14.7	65.2	5.2	9.1	52.9	55.9	39.8	61.1
	5.3	3.4	70.2	6.3	11.0	58.4	31.3	22.3	67.4
1999	1.3	0.8	33.3	2.0	3.5	30.5	2.2	1.6	22.5
	3.0	1.9	38.7	6.2	10.8	39.4	1.2	0.9	28.6
	6.8	4.3	44.0	9.3	16.2	44.6	5.5	3.9	34.6
	16.5	10.5	49.3	7.5	13.1	47.8	15.6	11.2	40.7
	34.3	21.8	54.6	8.5	14.8	50.9	32.7	23.4	46.7
	49.3	31.3	59.9	10.2	17.8	54.1	48.9	35.1	52.7
	37.7	24.0	65.3	8.7	15.2	57.3	29.5	21.1	58.8
	8.5	5.4	70.6	4.9	8.6	61.9	3.9	2.8	64.9

Table II:

WHEAT YIELD STATISTICS

	Reference Yield (bushels/ Acre)							
	1999	1998	1996	1994	1993		1992	1991
Field A								
Minimum	30.66	32.90	10.05	22.04	22.26		19.22	18.42
Maximum	73.19	72.64	34.16	58.86	69.92		30.71	38.21
Average	54.11	58.53	24.67	48.89	54.78		25.44	27.29
Field B								
Minimum	25.06	33.96	12.09	9.18	22.73	18.84	9.86	20.81
Maximum	64.81	61.99	53.75	43.62	65.12	49.16	29.53	58.98
Average	50.15	45.59	28.59	17.80	44.96	33.10	15.65	40.28
Field C								
Minimum	19.39	19.66	12.22	19.90	22.58	27.99	15.76	20.00
Maximum	67.45	70.18	48.75	45.12	41.42	68.41	32.54	55.91
Average	50.01	58.14	35.51	36.41	32.24	54.74	26.06	36.90

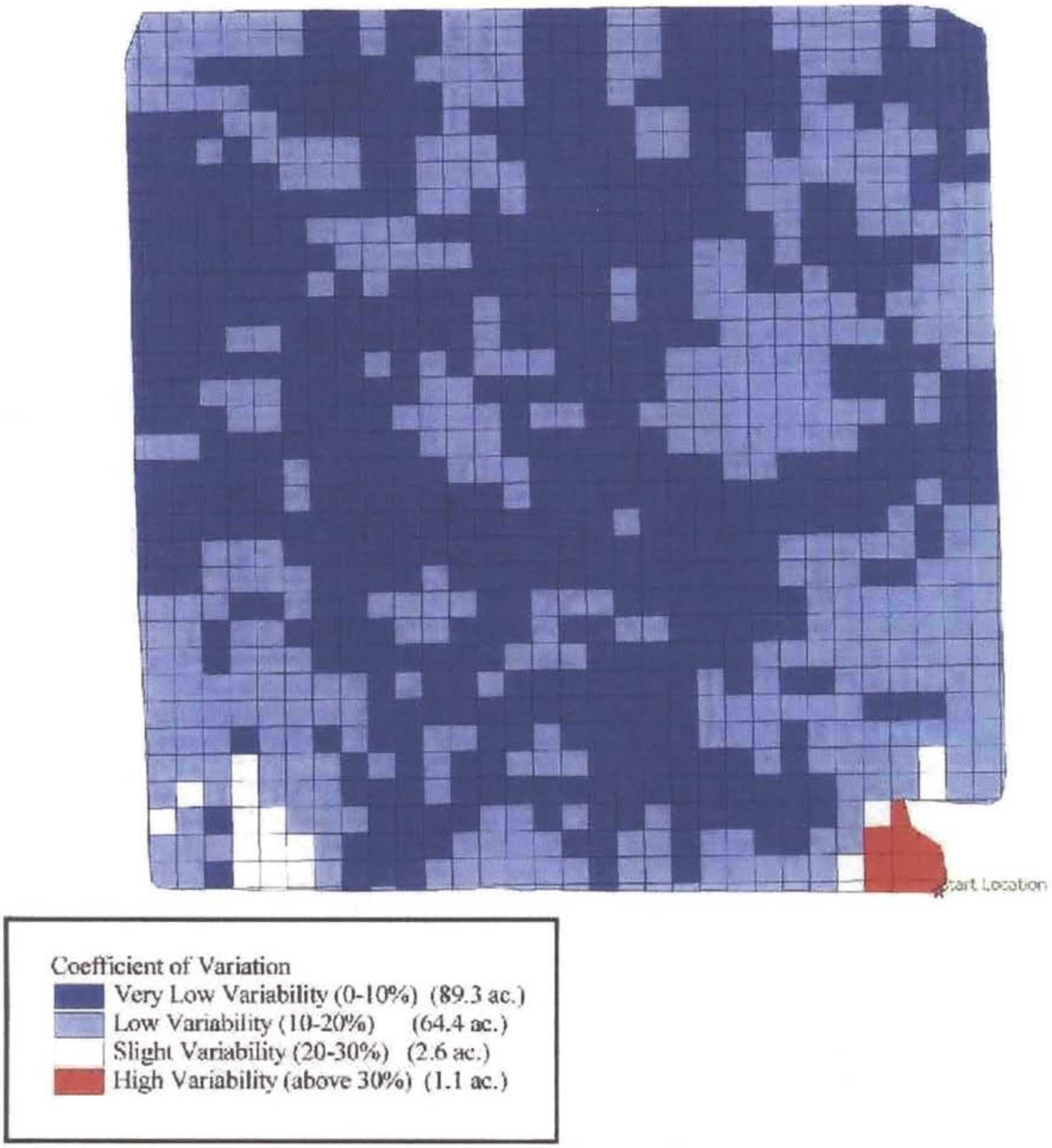

Figure 1: YIELD VARIABILITY MAP FOR FIELD A

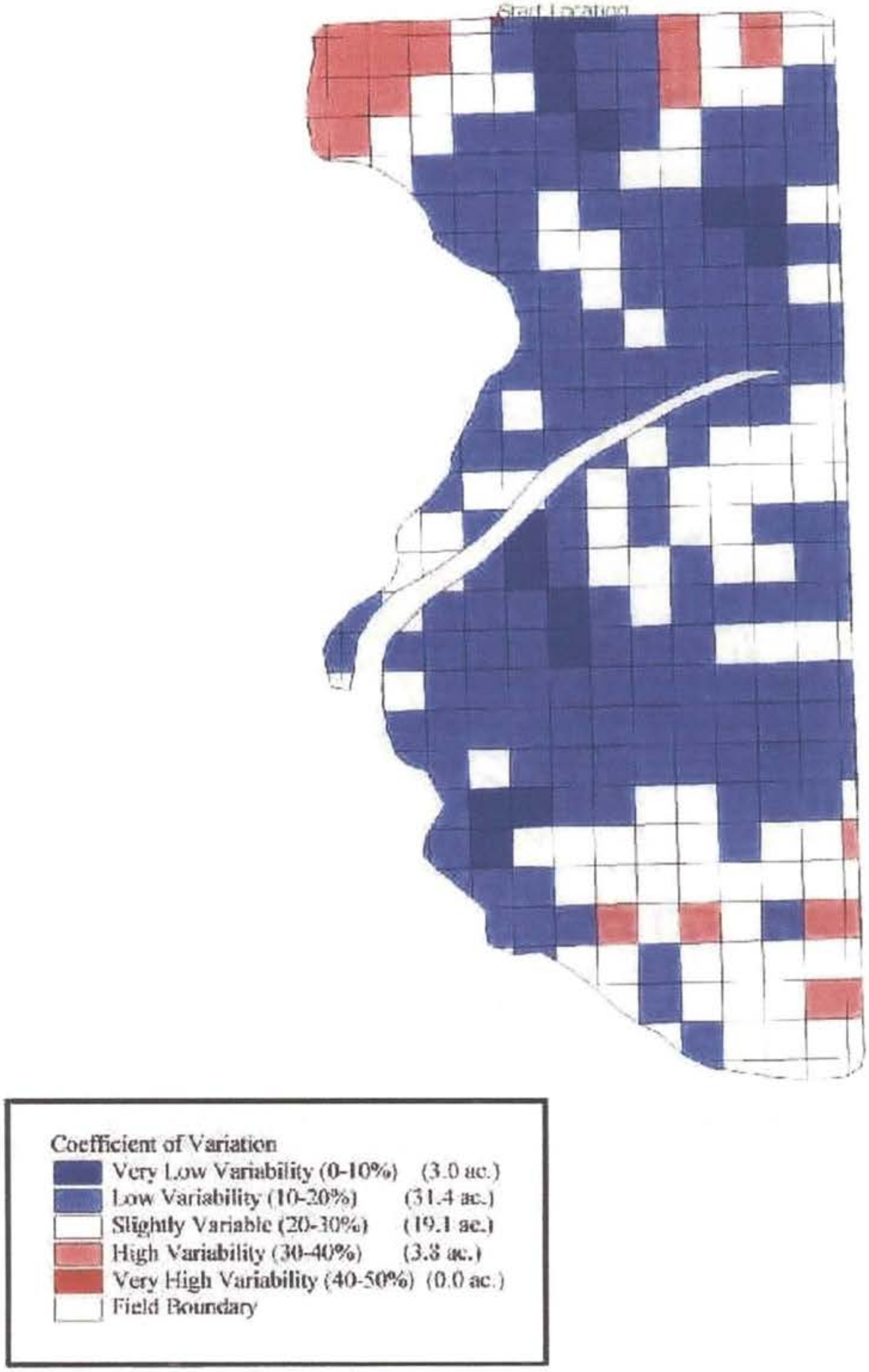

Figure 2: YIELD VARIABILITY MAP FOR FIELD B

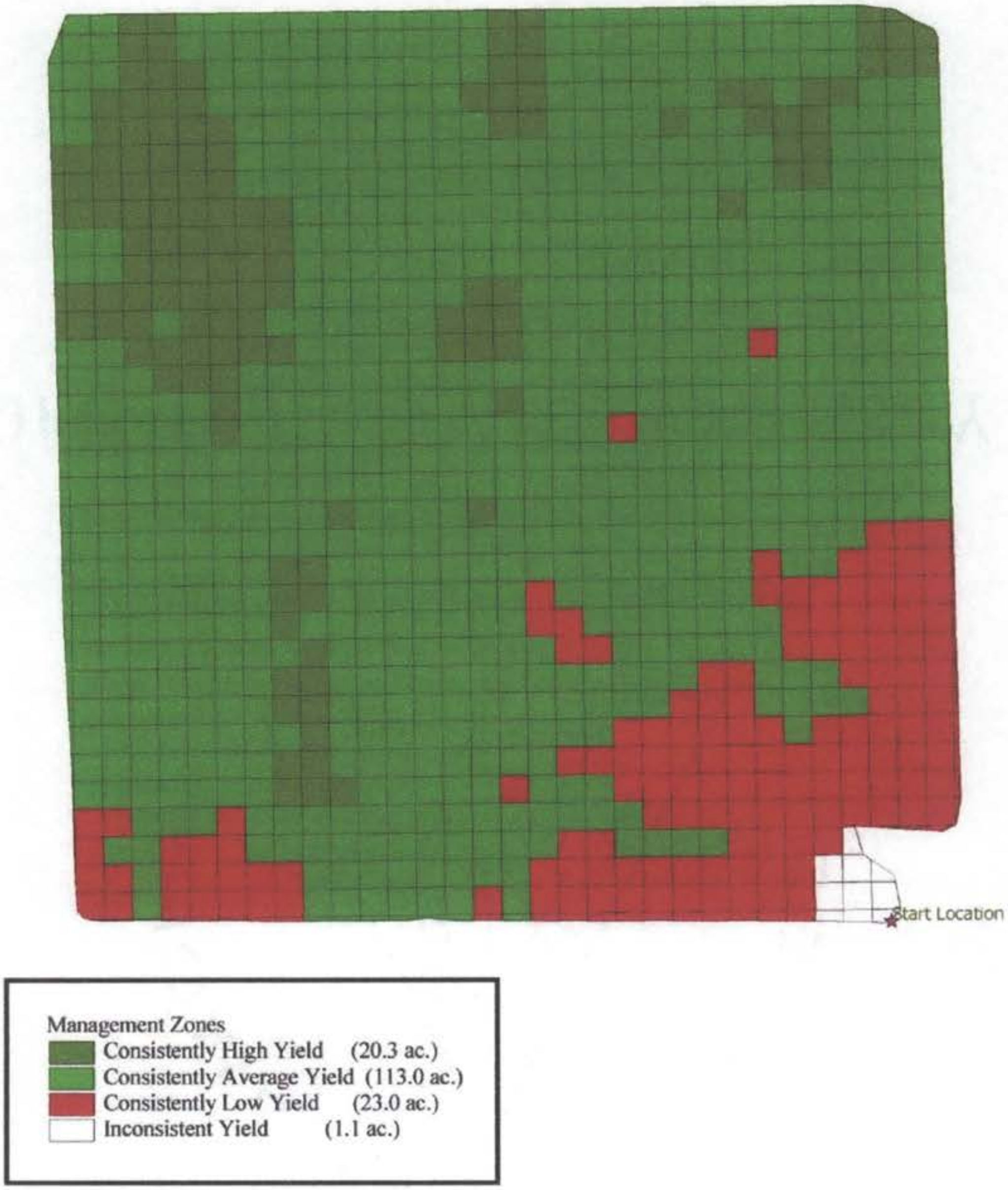

Figure 3: MANAGEMENT ZONES FOR FIELD A

Figure 4: MANAGEMENT ZONES FOR FIELD B

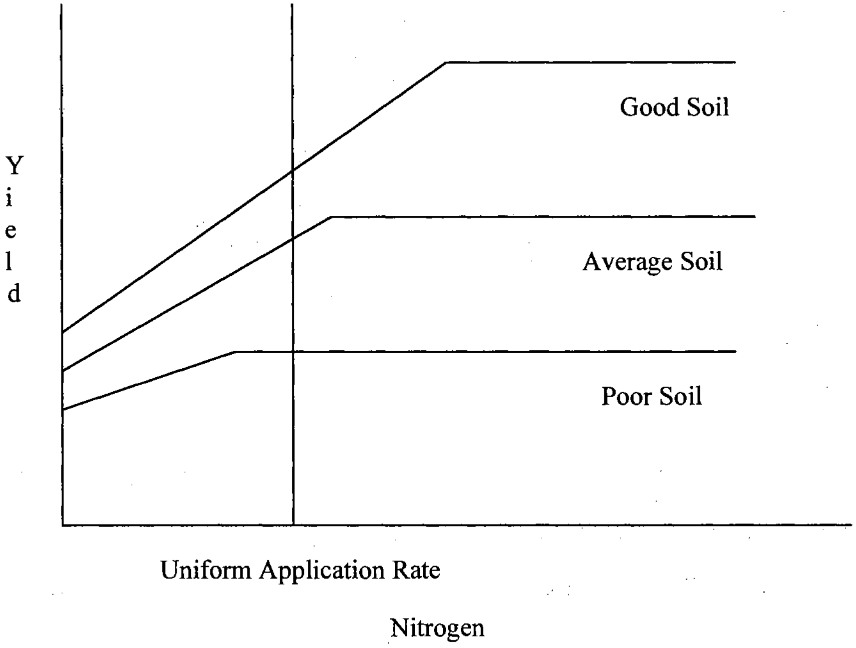

Figure 5: NITROGEN RESPONSE FUNCTIONS
FOR DIFFERENT SOIL TYPES

CHAPTER IV

Identification and Analysis of Spatial and Temporal Variability in Wheat Yields Using Satellite Images

Introduction

Farmers have traditionally applied inputs, including fertilizer, uniformly to achieve a yield goal. Farm management practices generally have been tailored to address soil deficiencies, pests, tillage practices, and irrigation problems at the field level. Reasons for this approach include the convenience and ease of management, as well as lack of resources to study the yield variability at the field level. However, the availability of analytical and physical tools to better understand and address variability, coupled with heightened interest in farming-related environmental issues, have increased the importance of research on the subject.

Yield variability is an important factor that affects farmers' profitability. Crop yields vary substantially across the field, or spatially, and from year to year, or temporally. Tools like yield monitors and satellite images have simplified the task of studying spatial and temporal variability. Variability analysis forms the diagnostic component of site-specific management. Results from the diagnostic component can be used in determining the applicability of various levels of the available technology.

Yields typically vary from one point in the field to another point during any given year. The spatial variability can be mostly attributed to the geo-spatial characteristics of the field. Interaction of physical features of the field, like soil compaction, elevation, and micro-climatic factors, plays an important role. Historic data on micro-climatic factors are, however, not readily available.

Another aspect of yield variability is temporal. The yield for any given point in the field will typically vary from year to year. Most of the temporal variability comes from climatic factors like rainfall and temperature changes. Management practices that vary from year to year can contribute to temporal variability.

Most of the research work on yield variability has focused on spatial variability. Yield monitors have typically been used to estimate spatial variability. However, use of yield monitors limits the amount of information available to the actual number of years that the monitor was used. Satellite images, on the other hand, relax the data availability restriction. The images are usually available for as many as ten years from various satellite vendors. Using an appropriate index, the images can be calibrated to give reliable estimates of yields at the field level. The per acre cost of acquiring satellite images, once made available at a commercial level, is probably much lower than the cost of yield monitors.

Most of the variability studies have focused on relatively high value crops, like corn and soybeans, and few have included wheat. However, wheat is a very important crop for Oklahoma's agricultural economy. In recent years, the value of production of winter wheat has exceeded that of any other crop (OASS Crop Value Reports). Also, wheat and products classified as a group generated the largest amount of Oklahoma export revenues.

Hence, the scientific community and Oklahoma wheat producers are interested in the economics of site-specific management in wheat. However, low wheat prices and net returns raises questions regarding the affordability of the precision farming technology and practices that appear to be economic for some higher valued crops.

Review of Literature

Yield variability across the field has generated much interest among researchers. Most often soil properties, in relationship with soil water holding capacities, have been cited as the major constraints to predicting crop yield.

Sudduth *et al.* identified soil depth and elevation as the two variables with a consistent effect on soybean yields. They reported a lack of correlation between soil fertility and yield due to a complex, non-linear relationship between yield and soil properties. In another multi-year work on yield variability, Lamb, Anderson and Rehm found little yield stability between years on the two experimental plots of continuous corn or corn in rotation. Carr *et al.* studied the crop yield differences between contrasting soils within fields, and compared economics of farming soils (in a site-specific management sense) and not fields. They concluded that farming soils resulted in an increased profitability as compared to farming the fields.

Wibawa *et al.* determined the changes in yield and net returns in response to fertilizer applications to manage the field variability. Their results indicated that a 50-foot grid sampling gave a good estimate of soil fertility variability in the field but resulted in lower net returns due to the added cost of soil sampling and testing. They also found that soil fertility varied over short distances and 50-foot grid soil sampling resulted in greater yield than a 250-foot grid sampling. Franzen and Peck aimed at determining the number of samples to be taken from a field so as to locate and describe major areas of fertility affecting variable rate fertilizer application. After comparing different grid values, they concluded that a sample density of at least 220-foot grid is important for fields with high soil variability if fertilizer application is to be effective in correcting deficiencies while avoiding costs due to excessive over application. Sample density would not have to be so high for fields with little variability, or high variability with all values in a high category. They recommended that sampling in a 220-foot grid would be a good procedure to test field variability when beginning a site-specific program. Density of future sampling can be tailored based upon the results obtained from the first stage.

Chancellor and Goronea studied the effects of spatial variability of nitrogen, moisture, and weeds on the advantages of site-specific applications for wheat. They collected field data for the three variables at one-meter intervals to form a basis for evaluating differences between the traditional and site-specific applications of water, nitrogen and herbicide. They compared the efficiency of input use with spatially variable applications at high, medium and low application rates. Highest efficiency gains were obtained at low and intermediate application rates. Those increases amounted to 2, 12 and 40 per cent for simulations of spatially modulated applications of water, nitrogen and herbicide, respectively, on irrigated wheat. They noted a decrease in the advantages with sampling and response intervals longer than one-meter.

In a recent economic analysis, Roberts, English and Mahajanashetti illustrate the potential benefits of variable rate nitrogen application and identify information needs. Lower costs, higher prices, and divergent yield response potentials were found to reduce the spatial variability required for profitable variable rate application. Information needs include sub-field yield response functions, prices, field spatial variability, and the cost of precision farming services. Also, Mahajanashetti, English, and Roberts use a theoretical model to identify ranges of spatial variability required within multiple-land-class fields for economically viable variable rate technology (VRT) and the spatial variability required for maximum return to VRT. They illustrate that the return to VRT, and the viable range of spatial variability, increases for higher corn and nitrogen prices.

Swinton and Ahmed in their survey of farmers' profitability from investment in precision agriculture equipment found that yield monitors are the precision technology most widely purchased by farmers. High costs of some processes and equipment, like grid soil sampling and variable rate technology controllers, was a major source of concern among the farmers.

Few economic studies have used satellite remote sensing to predict crop yields at the field level, or to measure spatial and temporal yield variability. This study uses satellite remote sensing and sophisticated precision farming GIS software to produce maps that show wheat yields and yield variability at the field level for the period 1991 to 1999. The maps reveal considerable spatial variability for a given field and year, and considerable temporal yield variability for a given field from year to year. The three-part data analysis includes study of variability at pixel-level, comparison of cost and return estimates for uniform versus site-specific applications of nitrogen fertilizer based on measures of spatial and temporal yield variability derived from satellite images, and statistical analysis of variance.

Methodology

Satellite remote sensing is often used to obtain information on the physical characteristics of the earth's surface. Vegetation indices such as the Normalized Difference Vegetative Index (NDVI) have been used widely as an indirect measure of crop biomass and yield. NDVI is calculated from the reflectance values of the red and near infrared (NIR) wavelength bands, using the following equation (Itenfisu *et al.*):

$$NDVI = \frac{(NIR - \mathrm{Re}\,d)}{(NIR + \mathrm{Re}\,d)} \tag{1}$$

As the green biomass of the canopy increases, reflectance in the red band portion of the spectrum decreases due to absorbance for photosynthesis. At the same time, that in the near infrared band increases due to the internal structure of the leaves. The accumulated dry matter of a given crop at a given stage of growth is the result of the crop carbon dioxide intake, soil moisture uptake and net photosynthetic assimilation. Since NDVI is a measure of the photosynthetic activity of the vegetation, it is related to the crop potential yield and thus appears suitable for yield estimation.

To validate NDVI for this analysis, a single springtime Landsat Thematic Mapper (LTM) scene was acquired for north central Oklahoma for each of eight years during the 1990's. The dates of the selected scenes corresponded approximately to the heading stage of winter wheat in Oklahoma. The LTM data were converted to reflectance NDVI using established procedures. Multi-year yield data from university research plots were used to calibrate an exponential relationship between NDVI at the heading stage and final wheat grain yield. This relationship was independently tested using six years of yield data obtained from each of two farm cooperators with fields located near the calibration site. The prediction equation was estimated as:

$$Y = 165.9e^{4.0443NDVI} \tag{2}$$

where Y is wheat grain yield in kg/ha. The performance of the prediction equation at these field sites was quite encouraging, especially considering that a single equation was used across years and that the crop's yield potential can change between the satellite overpass and harvest dates. A detailed discussion of the calibration and validation procedures is presented in Itenfisu *et al.*

For this economic analysis, three farm cooperators were identified in the area of north central Oklahoma covered by the satellite images. The cooperators identified a field and made available detailed records of input usage and wheat yields for the years for which we had satellite images. The field was then geo-referenced and located precisely on the satellite images. Sophisticated precision farming GIS software developed by SST Corporation was used to interpret the satellite images. The calibrated NDVI images were interpreted for the field and calibrated to the operator's actual yields. Then, a color map was prepared for each of several years for which a clear satellite image was available. Each map showed areas in the field for which wheat yields were predicted to be within specified bushel-per-acre ranges and indicated the average wheat yield per acre for that field and year.

Each map is composed of many small pixels. The size of pixel indicates the resolution of the image and the amount of information contained therein. Smaller pixels in most cases are preferred to large one. In our case, the size of a pixel was approximately 0.1544 acre. Hence we can get the estimated yield information for almost every one-sixth of an acre. Since each of the pixels is geo-referenced, with unique latitude and longitude coordinates, yield estimates for unique pixels can be calculated and compared for different years.

One of the advantages of using satellite imagery is that we can obtain yield estimates for years for which we do not have much field-level information. However, inclement weather conditions, like clouds at the time when the image is taken, can render it useless for our purpose. The producers provided detailed information regarding the machinery and equipment complement, tillage operations, seeding rates, fertilizer practices, use of insecticides and herbicides, and custom harvesting costs for budgeting analysis.

Enterprise budgeting methods (Petermann *et al.*) are used to compare the costs and returns associated with uniform applications of nitrogen across the field and site-specific applications of nitrogen. In analyzing uniform applications of nitrogen, the field is assumed to receive the quantity recommended by agronomists to produce a 50 bushel-per-acre yield goal and to achieve the average yield actually achieved in a given year. In analyzing site-specific applications, each micro-unit within the field is assumed to receive the pounds per acre recommended by agronomists to produce the average yield in that unit. For some areas of the field, the nitrogen application is greater than, and in other areas it is less than, that used in the analysis of uniform applications.

Results and Discussion

For the fields A, B, and C, the acreages are 157.3, 57.3 and 139.7 acres respectively. Field A is relatively homogenous in terms of soil type and elevation, field B has more physical variability with terraces and different soil types, and field C has two basic soil types, but is relatively level. Eight years of estimated yield data are available for field C. For fields A and B, however, information was available only for seven years. One of the years could not be used due to cloudy conditions in each of the two cases.

The estimated yield maps are an interesting initial result of the analysis. The yield maps for those fields contain 1098, 432 and 993 pixels respectively. However, the numbers of pixels included in the analysis were reduced to 963, 286, and 857 respectively, after excluding the irregular-sized pixels on the border of each whose values were influenced by pixels outside the field boundary. For illustration, the 1999 yield map derived from satellite data for the three fields are shown as figures 1-3.

For any given year of data, the pixels are grouped into eight equally spaced yield ranges. For the eight yield ranges identified on the yield map, the average yields vary considerably from the minimum to the maximum. Acreage and yield information for three selected years for each field is shown in table I. For example, yields range from 11.6 bu/ac to 32.7 bu/ac for field A in 1996. However, these low and high yield ranges represent a very small part (9.8 acres or 6.2 percent) of the field. The three yield ranges with average yields of 23.6, 27.1, and 30.1 bushels per acre represent about 77 percent of the field. For field B in 1996, the yield ranges with average yields of 15.5, and 18.4 bushels per acre make up for more than half (about 52 per cent) of the field. In the case of field C for the same year, three yield ranges with average yields of 34.2, 37.4, and 40.5 bushels per acre represent about 84 percent of the field. The average yields follow similar pattern for the three fields during the time period of that data. This point takes on additional significance when we discuss site-specific management of the field.

For each of the three fields, pixel level statistics are given in tables II-IV. For field A, the pixel yield ranged from a minimum of 10.05 bu/ac (1996) to a maximum of 73.19 bu/acres (1999) over the past seven years. For field B, the pixel yield varied from 9.18 bu/ac (1996) to 65.12 (1994). In case of field C, a minimum of 12.22 bu/ac (1997) and a maximum of 70.18 bu/ac (1998) comprised the pixel yield range. Thus, for each of the fields the range of yields obtained across the field is very high. The annual average yields for the three fields also vary substantially over the period studied (from 24.67 bu/ac to 58.53 bu/ac for A, from 15.65 bu/ac to 50.15 bu/ac for B, and from 26.06 bu/ac to 58.14 bu/ac for C). The factors causing this variation are spatial for a given year and temporal across the years.

The annual coefficient of variation ranges from 0.07 (1992) to 0.16 (1999) for field A, from 0.14 (1999) to 0.34 (1996) for field B, from 0.09 (1992, 1993) to 0.18 (1991) for field C. The coefficients of variation indicate that the data for the most part are relatively equally variable about the annual means. For field B, particularly, higher coefficients of variation tend to be associated with lower average yield years.

Pixel-by-Pixel Analysis:

To further analyze spatial yield variability, individual pixels were studied intensively. Using 1999 as the base year, the multiple-year yield data set for each of the fields was sorted from lowest- to highest-yielding pixels. Pixels were chosen from the sorted data sets using fixed intervals from the entire yield range. Yield estimates for the chosen pixels were ranked from the lowest to the highest across the years. Assuming that there is an equal chance of obtaining any of the yields, each of the estimates was assigned an equal probability of occurrence. Then, cumulative probability distribution functions were developed for a typical high yield and low yield pixel in each field. For illustration purpose cumulative probability graphs for the two pixels for each of the fields are presented in figure 4. The cumulative probability graphs for each of the fields reveal that for most of the pixels across field A, regardless of location, the probability of obtaining a yield of 30 bu/acre yield lies somewhere between 0.40 and 0.50. There is a similar probability of getting a yield of 25 bu/ acre for field B and a yield of 35 bu/acre for field C. Thus, almost all of the pixels in each field, even those with extremely low yield during the base year 1999, have almost a fifty percent probability of producing a level of output much higher than the one actually achieved in 1999.

As an alternative to the earlier procedure, the data sets were sorted again using average yield across years as base. Pixels were chosen to plot cumulative probability function as before. For majority of chosen pixels for field A, the probability of obtaining a yield of 30 bu/ac or less is still between 0.40 and 0.50. However for field B and C, the probability of an achieving a higher yield increased for pixels with greater average yield across years. The phenomenon was more pronounced in the case of field B, due to its smaller size and relatively higher variability. In case of field C, however, probability of obtaining a yield of 35 bu/ac or less for most of the pixels had is still somewhere between 0.40 and 0.50. It shows that areas of different yield potential can possibly be identified using cumulative probability plot method.

Budgeting Analysis:

If we assume, as many previous studies have, that spatial yield variability is caused by nitrogen deficiency, then uniform versus site-specific practices can be compared. The operators provided detailed information regarding the machinery and equipment complement, tillage operations, seeding rates, fertilizer practices, use of insecticides and herbicides, and custom harvesting costs. Based on this information, detailed per acre cost and return budgets were developed for the fields to compare uniform application of nitrogen with variable rate management. Each of the fields was divided into eight micro-units based on estimated yields. The idea is to manage each of the micro-units to achieve a site-specific yield goal, at an assumed cost of $4.5 per acre, rather than treating for the whole field average yield. Variable rate management will be economically feasible only if the savings in input application exceed the additional costs incurred.

An alternative variable management scenario was also studied. In this case, the micro-units with yields below the average yield for the whole field were treated with fertilizer applications based on the actual yield goal, hence reducing the quantity of fertilizer applied on those micro-units. However, all the micro-units with yields above the whole-farm average yield were treated with fertilizer application based on the whole-farm average yield. This is based on the assumption that since uniform fertilizer application on those micro-units will produce the yields greater than the whole-farm average on those micro-units, it is efficient to fertilize them based on the whole-farm average yield goal. Hence, the whole-farm average yield is the maximum yield goal for fertilizer application for a given field. In this way, the total fertilizer application under variable rate management with a ceiling level will result in an overall decrease in the amount of fertilizer applied.

The estimated budget values for uniform versus variable rate application for the three fields for 1999 are presented in tables V-VII. Notice that total fertilizer consumption increases slightly when managed variably in all three cases, leading to higher costs than for uniform nitrogen application. However, variable rate application with ceiling leads to a total reduction in the fertilizer application, and decrease in the total operating costs. However, the variability across the field for the given year is not large enough to warrant the use of precision farming a cost of $4.5 per acre.

The shape of the wheat yield-nitrogen response function is important. Crop and soil scientists provided the response function used to calculate the nitrogen requirements for the different yield goals (Zhang *et al.*). When plotted within the yield range of interest, the function is approximately linear (figure 5). Thus, a weighted-average of the nitrogen requirements for the micro-unit yield goals (without a ceiling) is almost same as the nitrogen requirements for the whole field based on the average yield goal. Hence, variable-rate fertilizer applications without taking into account the whole-farm yield average would reduce neither the amount nor the cost of fertilizer applications. The additional cost of variable-rate management, thus, increases the total costs of site-specific farming vis-à-vis the uniform approach. A nitrogen response function that increases at a decreasing rate could result in a different comparative profitability statement.

However, the spatial variability in the fields does not appear to be related to fertilizer deficiencies or other inputs identified in previous studies. Thus, managing spatial variability appears challenging and satellite images may not provide good managers with uniform soils much opportunity to increase returns through precision farming.

Analysis of Variance:

To further investigate this possibility, statistical procedures were used to estimate the significance of variables representing time and space. A variable 'year' is used for years of data availability across the field. Another variable 'site' represents each of the pixels across years. The dependant variable, 'yield', contains the information regarding the yield in bu/acre for a particular pixel for a particular year. The 'year' variable includes the effect of variability due to meteorological factors while the 'site' variable includes the effect of variability due to site-specific factors. A simple means model (equation 3) was specified and estimated using the GLM procedure in SAS, describing yield as a function of fixed year and site variables.

$$Y_{ij} = \mu + \tau_i + \rho_j + \varepsilon_{ij} \qquad (3)$$

where Y_{ij} = yield in bushels per acre for pixel i in year j, μ = general mean, τ_i = dummy variable for pixel i, and ρ_i = dummy variable for year j.

Table VIII summarizes the result of the analysis. High R^2 values indicate that the dummy variables used account for most of the variability in yields across time and space. Both of the variables are significant, however the F-test value for time is much greater than that for the location variable. It appears that the year variable, representing temporal variability, is responsible for most of the yield variation in all the fields.

It would be helpful to include soil types and other physical characteristics of the fields to better explain the spatial variability. Due to the availability of appropriate information from the producer and yield maps, Field B was used for soil type analysis. The whole field was divided in to six distinct units based on soil types. The pixels lying in each of the group were identified and each of them was assigned a 'Soil type' value (from 1 to 6) unique to that group. The simple means model was re-specified, now describing yield as a function of fixed year and soil variables. The results are presented in table IX. The R^2 value drops from 0.9007 to 0.8524 when the soil variable replaces the site variable. In the new model, both of the variables are significant again. Although there is no improvement in the model specification when the soil type variable is used, it the significant R^2 value shows that soil type is a very significant variable. The overwhelming temporal variability may be further explained by including weather-related variables, like rainfall, in the model. The results presented in table X for field C do not show any increase in explanatory power after the weather variable is included in the model, as the R^2 value stays essentially the same. It also shows that the rainfall is a very significant variable in defining temporal variability.

The evidence of high temporal variability, however, emphasizes the importance of the time of availability of satellite imagery to the farm decision-maker. Resource-usage at the farm level could be improved if the images were available when management practices could be tailored to the expected output. For example, an indication of lower than average yields due to weather-related events could lead the farmer to reduce spring fertilizer applications uniformly or in a site-specific pattern to reduce input costs and moderate the decline in net returns per acre. However, this information would have to be available much earlier in the growing season than the satellite images used in this analysis.

Although the use of more variables to explain variability is desirable, it might not be very practical since we are focusing on smaller units of the same field. Climatic information at a micro-unit is difficult, if not impossible, to obtain. The micro-climatic information may help explain variability, but its usefulness in reducing yield variability may be limited.

Conclusions

The variability in wheat yields over time and space is substantial. However, the low value of the crop may leave few alternatives to managers attempting to manage yield variability. Satellite imagery provides an opportunity to study the spatial and temporal yield variability on the farmers' fields at low cost. The costs of accessing the information are expected to decrease with advancement and commercialization of the technology.

Fields with highly variable yields resulting from soil variations and manageable inputs will gain the most from this technology. Such soils can perhaps be more efficiently managed through spatially variable technologies. However, their potential usefulness in less variable fields needs further investigation. Perhaps excellent managers who are using annual soil tests to insure that fertilizer deficiencies do not exist should be told that site-specific management of inputs in wheat production is probably not economic for these uniform fields.

An approach that would benefit some producers is to identify patterns of yield consistency and inconsistency in different parts/micro-units of each field. Costs of site-specific management can be reduced if those distinctly behaving parts of the field are relatively large in size. Smaller and numerous micro-units may make precision farming economically infeasible, especially in case of a crop like wheat.

There are some important issues that need to be addressed to make the satellite-generated information more beneficial for wheat producers. The time that the satellite images are taken is very important. Farmers tend to tailor their farm management practices based on the information that becomes available during the course of crop production. For example, if the satellite images, and yield estimates could be made earlier in the growing season, the farmer might be able to customize their fertilizer applications. Perhaps they could reduce the cost of fertilizer in cases where the satellite images forecasts a bad crop.

The study of satellite images for a given field for a number of years can make the farmer more aware of problem areas within their fields. The images can reveal change in the spatial yield variability pattern through time as a result of the farm tillage and management practices. Farmers could decide to change tillage or other input practices to increase yields in certain areas.

Availability of climatic information, like rainfall, for different micro-units could be important in analyzing spatial and temporal variability. However, obtaining information on microclimates could be costly. Also, while it might help explain yield variability, producers would likely still find it difficult to manage weather-related variability.

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Table I:

AVERAGE YIELD RANGES FROM YIELD MAPS

	Field A			Field B			Field C		
Year	Area		Yield	Area		Yield	Area		Yield
	Acres	%age	(bu/ac)	Acres	%age	(bu/ac)	Acres	%age	(bu/ac)
1996	1.3	0.8	11.6	3.6	6.3	10.1	0.8	0.6	21.5
	3.0	1.9	14.6	5.3	9.2	11.9	2.0	1.4	24.7
	6.8	4.3	17.6	7.9	13.8	13.6	2.7	1.9	27.9
	16.5	10.5	20.6	13.4	23.4	15.5	11.9	8.5	31.1
	34.3	21.8	23.6	16.5	28.8	18.4	37.4	26.8	34.2
	49.3	31.3	27.1	6.3	11.0	22.3	50.3	36.0	37.4
	37.7	24.0	30.1	1.3	2.3	27.5	29.7	21.3	40.5
	8.5	5.4	32.7	3.0	5.2	37.1	4.8	3.4	43.7
1998	1.2	0.8	35.4	3.1	5.4	33.1	0.4	0.3	22.9
	9.4	6.0	40.4	8.4	14.6	37.1	1.4	1.0	29.3
	24.3	15.4	45.3	9.2	16.0	40.6	3.1	2.2	35.7
	29.8	18.9	50.3	10.2	17.8	43.6	4.4	3.1	42.0
	27.9	17.7	55.3	8.6	15.0	46.5	14.4	10.2	48.4
	36.2	23.0	60.2	6.4	11.1	49.5	29.7	21.1	54.7
	23.2	14.7	65.2	5.2	9.1	52.9	55.9	39.8	61.1
	5.3	3.4	70.2	6.3	11.0	58.4	31.3	22.3	67.4
1999	1.3	0.8	33.3	2.0	3.5	30.5	2.2	1.6	22.5
	3.0	1.9	38.7	6.2	10.8	39.4	1.2	0.9	28.6
	6.8	4.3	44.0	9.3	16.2	44.6	5.5	3.9	34.6
	16.5	10.5	49.3	7.5	13.1	47.8	15.6	11.2	40.7
	34.3	21.8	54.6	8.5	14.8	50.9	32.7	23.4	46.7
	49.3	31.3	59.9	10.2	17.8	54.1	48.9	35.1	52.7
	37.7	24.0	65.3	8.7	15.2	57.3	29.5	21.1	58.8
	8.5	5.4	70.6	4.9	8.6	61.9	3.9	2.8	64.9

Table II:

WHEAT YIELD STATISTICS: FIELD A

	Reference Yield (bushels/ Acre)						
	1999	1998	1996	1994	1993	1992	1991
Minimum	30.66	32.90	10.05	22.04	22.26	19.22	18.42
Maximum	73.19	72.64	34.16	58.86	69.92	30.71	38.21
Average	54.11	58.53	24.67	48.89	54.78	25.44	27.29
Standard Deviation	8.62	6.93	3.66	5.16	8.09	1.87	3.93
Coefficient of Variation	0.16	0.12	0.15	0.11	0.15	0.07	0.14

Table III:

WHEAT YIELD STATISTICS: FIELD B

	Reference Yield (bushels/ Acre)						
	1999	1998	1996	1994	1993	1992	1991
Minimum	25.06	33.96	9.18	22.73	18.84	9.86	20.81
Maximum	64.81	61.99	43.62	65.12	49.16	29.53	58.98
Average	50.15	45.59	17.80	44.96	33.10	15.65	40.28
Standard Deviation	6.88	6.80	6.07	8.36	5.31	3.69	7.50
Coefficient of Variation	0.14	0.15	0.34	0.19	0.16	0.24	0.19

Table IV:

WHEAT YIELD STATISTICS: FIELD C

	Reference Yield (bushels/ Acre)							
	1999	1998	1997	1996	1994	1993	1992	1991
Minimum	19.39	19.66	12.22	19.90	22.58	27.99	15.76	20.00
Maximum	67.45	70.18	48.75	45.12	41.42	68.41	32.54	55.91
Average	50.01	58.14	35.51	36.41	32.24	54.74	26.06	36.90
Standard Deviation	8.20	7.88	4.51	3.64	3.51	5.12	2.39	6.64
Coefficient of Variation	0.16	0.14	0.13	0.10	0.11	0.09	0.09	0.18

Table V:
UNIFORM VS.VARIABLE-RATE BUDGETS FOR FIELD A FOR YEAR 1999 (US $).

			Uniform		Variable Rate		Variable Rate w/Ceiling	
OPERATING INPUTS	Units	Price	Quantity	Value	Quantity	Value	Quantity	Value
Wheat Sead	Bu.	6.00	1.00	6.00	1.00	6.00	1.00	6.00
18-46-0 Fertilizer	Lbs.	0.12	50.00	6.00	50.00	6.00	50.00	6.00
Anhydrous Ammon.	Lbs.	0.11	137.39	15.25	137.39	15.25	127.40	14.14
Fertilizer Spreder	Acre	2.25	1.00	2.25	1.00	2.25	1.00	2.25
Glean	Oz.	19.00	0.30	5.70	0.30	5.70	0.30	5.70
Annual Operating Capital	Dol.	0.09	32.66	2.86	32.66	2.86	32.66	2.86
Machinery Labor	Hr.	6.50	5.00	32.50	5.00	32.50	5.00	32.50
Other Labor	Hr.	6.50	0.40	2.60	0.40	2.60	0.40	2.60
Machinery Fuel, Lube, Repaits	Dol.			21.71		21.71		21.71
						4.50		4.50
TOTAL OPERATING COSTS				94.87		99.37		98.26
FIXED COSTS		Amount	Value		Value		Value	
Machinery								
Interest	Dol.		11.17		11.17		11.17	
Depreciation, Taxes, Insurance	Dol.		16.23		16.23		16.23	
TOTAL FIXED COSTS				27.40		27.40		27.40
PRODUCTION	Units	Price	Quantity	Value	Quantity	Value	Quantity	Value
Wheat	Bu.	2.50	58.16	145.40	58.16	145.40	58.16	145.40
TOTAL RECEIPTS				145.40		145.40		145.40
RETURNS ABOVE TOTAL OPERATING COST				50.53		46.03		47.14
RETURNS ABOVE ALL SPECIFIED COSTS				23.13		18.63		19.74

Table VI:
UNIFORM VS.VARIABLE-RATE BUDGETS FOR FIELD B FOR YEAR 1999 (US $).

			Uniform		Variable Rate		Variable Rate w/Ceiling	
OPERATING INPUTS	Units	Price	Quantity	Value	Quantity	Value	Quantity	Value
Wheat Sead	Bu.	6.00	1.50	9.00	1.50	9.00	1.50	9.00
18-46-0 Fertilizer	Lbs.	0.12	50.00	6.00	50.00	6.00	50.00	6.00
Anhydrous Ammon.	Lbs.	0.11	110.97	12.32	112.90	12.53	103.66	11.51
Custom Harvest	Acre	12.00	1.00	12.00	1.00	12.00	1.00	12.00
Custom Harvest	Bu.	0.12	30.00	3.60	30.00	3.60	30.00	3.60
Custom Hauling	Bu.	0.12	50.00	6.00	50.00	6.00	50.00	6.00
Fertilizer Spreder	Acre	2.25	1.00	2.25	1.00	2.25	1.00	2.25
Glean	Oz.	19.00	0.30	5.70	0.30	5.70	0.30	5.70
Annual Operating Capital	Dol.	0.09	32.66	2.86	32.66	2.86	32.66	2.86
Machinery Labor	Hr.	6.50	4.00	26.00	4.00	26.00	4.00	26.00
Other Labor	Hr.	6.50	0.40	2.60	0.40	2.60	0.40	2.60
Machinery Fuel, Lube, Repaits	Dol.			12.24		12.24		12.24
						4.50		4.50
TOTAL OPERATING COSTS				100.56		105.28		104.25
FIXED COSTS		Amount	Value		Value		Value	
Machinery								
Interest	Dol.		12.98		12.98		12.98	
Depreciation, Taxes, Insurance	Dol.		19.58		19.58		19.58	
TOTAL FIXED COSTS				32.56		32.56		32.56
PRODUCTION	Units	Price	Quantity	Value	Quantity	Value	Quantity	Value
Wheat	Bu.	2.50	50.00	125.00	50.00	125.00	50.00	125.00
TOTAL RECEIPTS				125.00		125.00		125.00
RETURNS ABOVE TOTAL OPERATING COST				24.43		19.72		20.75
RETURNS ABOVE ALL SPECIFIED COSTS				-8.13		-12.84		-11.81

Table VII:
UNIFORM VS.VARIABLE-RATE BUDGETS FOR FIELD C FOR YEAR 1999 (US $).

			Uniform		Variable Rate		Variable Rate w/Ceiling	
OPERATING INPUTS	Units	Price	Quantity	Value	Quantity	Value	Quantity	Value
Wheat Sead	Bu.	6.00	1.50	9.00	1.50	9.00	1.50	9.00
18-46-0 Fertilizer	Lbs.	0.12	50.00	6.00	50.00	6.00	50.00	6.00
Anhydrous Ammon.	Lbs.	0.11	111.39	12.36	113.43	12.59	103.55	11.49
Custom Harvest	Acre	12.00	1.00	12.00	1.00	12.00	1.00	12.00
Custom Harvest	Bu.	0.12	30.17	3.62	30.17	3.62	30.17	3.62
Custom Hauling	Bu.	0.12	50.17	6.02	50.17	6.02	50.17	6.02
Fertilizer Spreder	Acre	2.25	1.00	2.25	1.00	2.25	1.00	2.25
Annual Operating Capital	Dol.	0.09	32.66	2.86	32.66	2.86	32.66	2.86
Machinery Labor	Hr.	6.50	3.49	22.69	3.49	22.69	3.49	22.69
Other Labor	Hr.	6.50	0.40	2.60	0.40	2.60	0.40	2.60
Machinery Fuel, Lube, Repaits	Dol.			12.35		12.35		12.35
						4.50		4.50
TOTAL OPERATING COSTS				91.74		96.47		95.37
FIXED COSTS		Amount	Value		Value		Value	
Machinery								
Interest	Dol.		14.66		14.66		14.66	
Depreciation, Taxes, Insurance	Dol.		21.88		21.88		21.88	
TOTAL FIXED COSTS				36.54		36.54		36.54
PRODUCTION	Units	Price	Quantity	Value	Quantity	Value	Quantity	Value
Wheat	Bu.	2.75	50.17	137.96	50.17	137.96	50.17	137.96
TOTAL RECEIPTS				137.96		137.96		137.96
RETURNS ABOVE TOTAL OPERATING COST				46.22		41.49		42.59
RETURNS ABOVE ALL SPECIFIED COSTS				9.68		4.95		6.05

Table VIII:

ANOVA TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	Pr>F
Field A					
Year	6	1368556.375	228092.729	10100.0	<.0001
Site	962	107068.860	111.298	4.93	<.0001
$R^2 = 0.918834$	Coeff Var = 11.32568				
Field B					
Year	6	326521.0611	54420.1769	2276.57	<.0001
Site	285	44163.2804	154.9589	6.48	<.0001
$R^2 = 0.900679$	Coeff Var = 13.82625				
Field C					
Year	7	798046.9792	114006.7113	4208.74	<.0001
Site	856	52761.0435	61.6367	2.28	<.0001
$R^2 = 0.839790$	Coeff Var = 12.61653				

Table IX:

ANOVA TABLE: FIELD B (SOIL TYPES)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	Pr>F
Year	6	326521.0611	54420.1769	1782.74	<.0001
Soil	5	24292.9577	4858.5915	159.16	<.0001

$R^2 = 0.852399$ Coeff Var = 15.62430

Table X:

ANOVA TABLE: FIELD C (RAINFALL)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	Pr>F
Year	0	0	.	.	.
Site	856	52761.0435	61.6367	2.28	<.0001
Rainfall	0	0	.	.	.

$R^2 = 0.839790$ Coeff Var = 12.61653

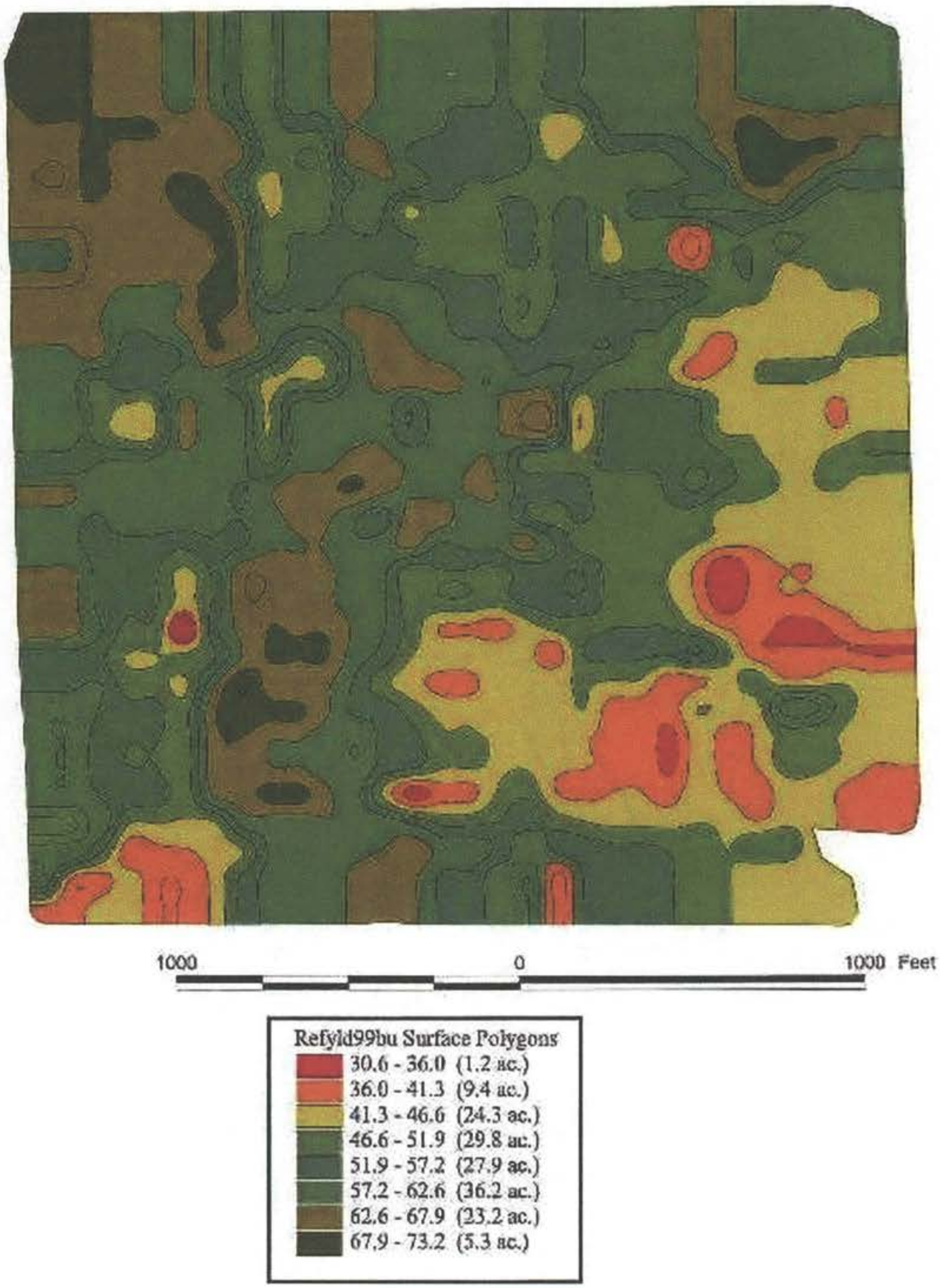

Figure 1: YIELD MAP FOR 1999: FIELD A

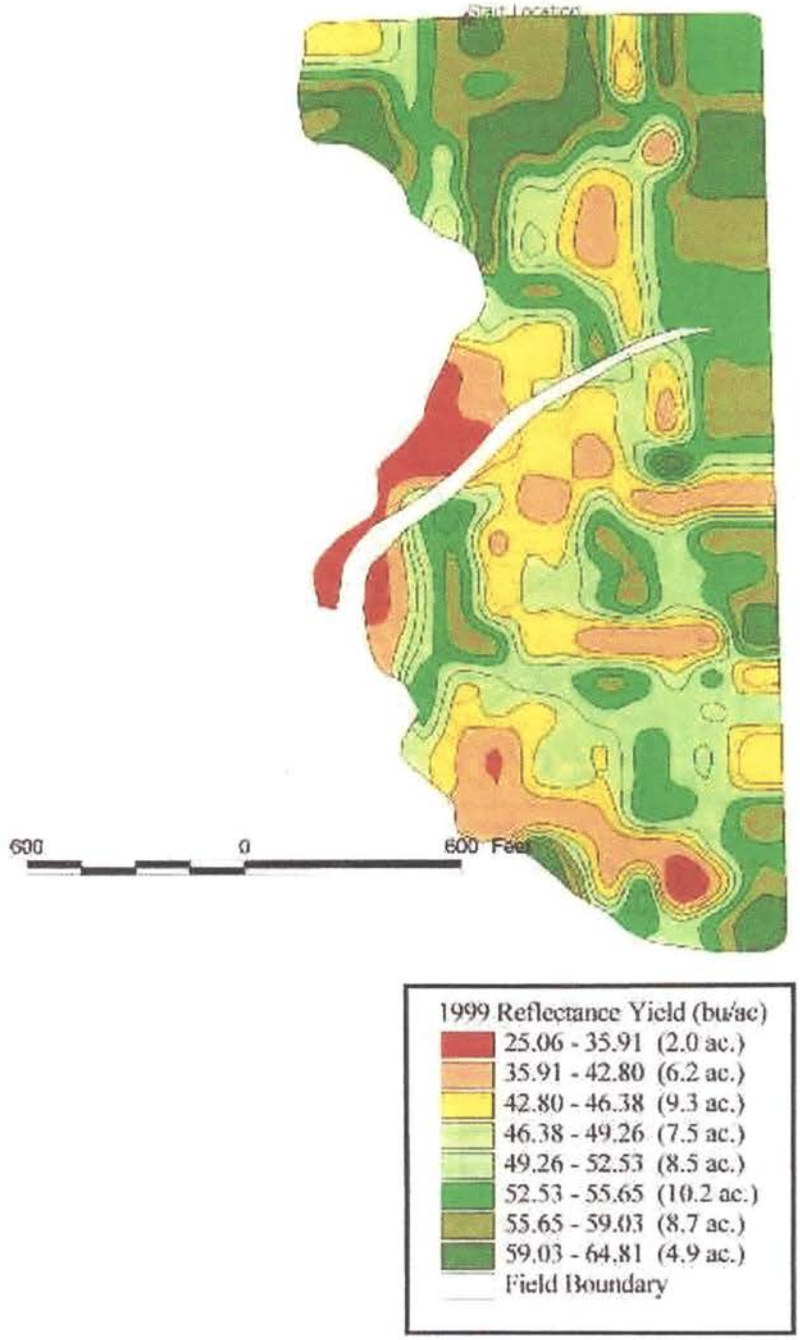

Figure 2: YIELD MAP FOR 1999: FIELD B

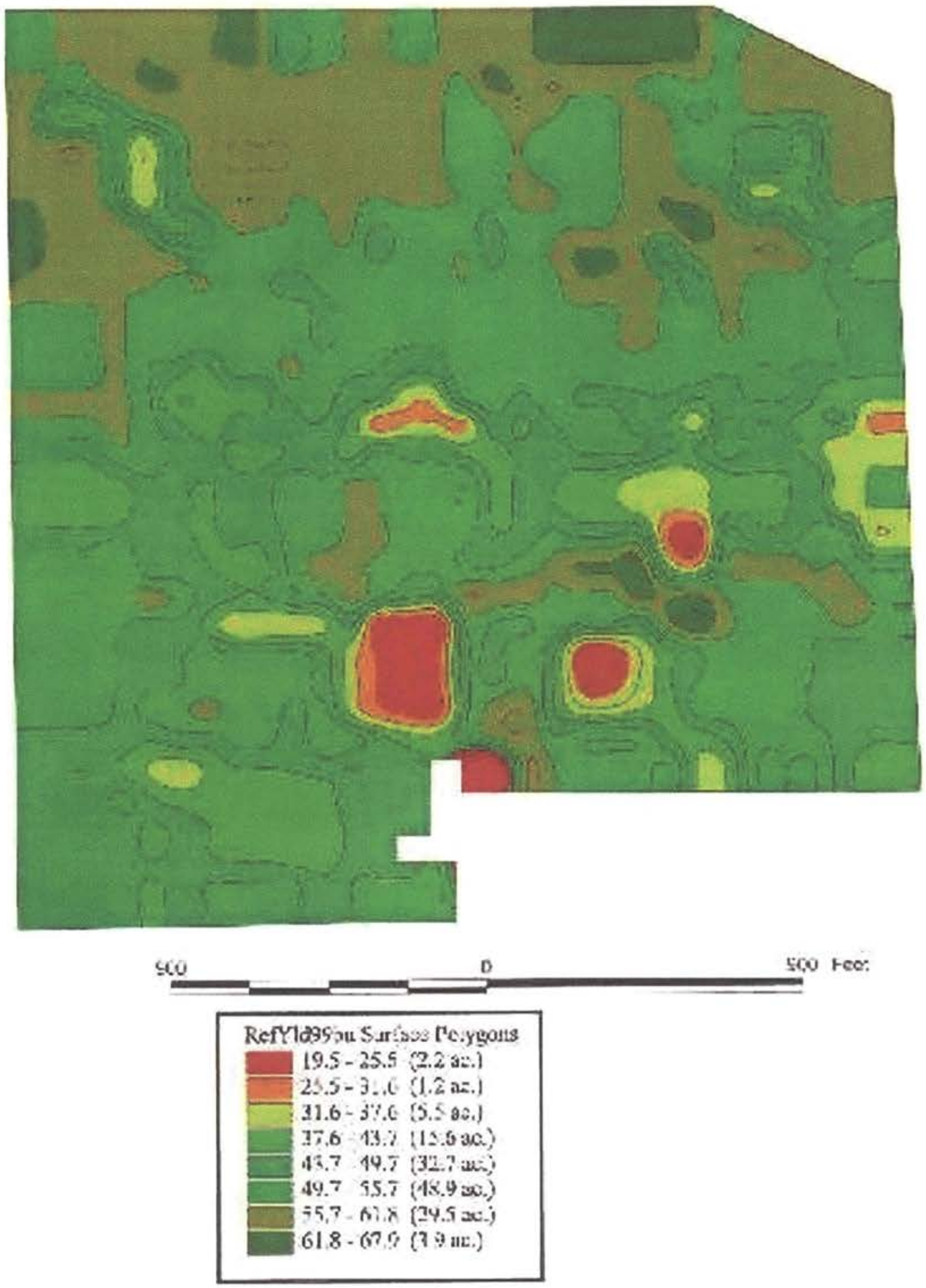

Figure 3: YIELD MAP FOR 1999: FIELD C

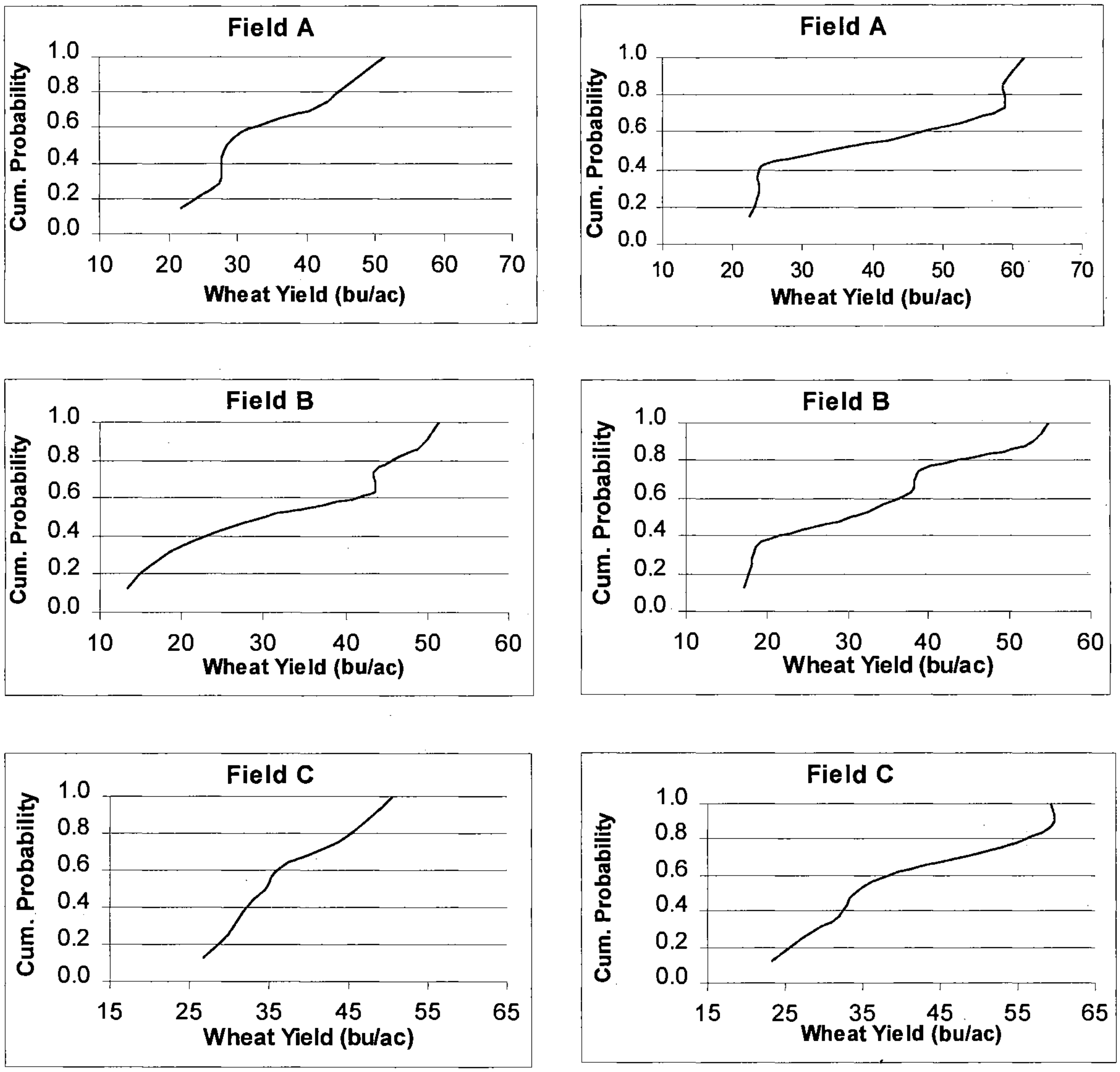

Figure 4: CUMULATIVE PROBABILITY GRAPHS FOR
TWO PIXELS FOR EACH FIELD

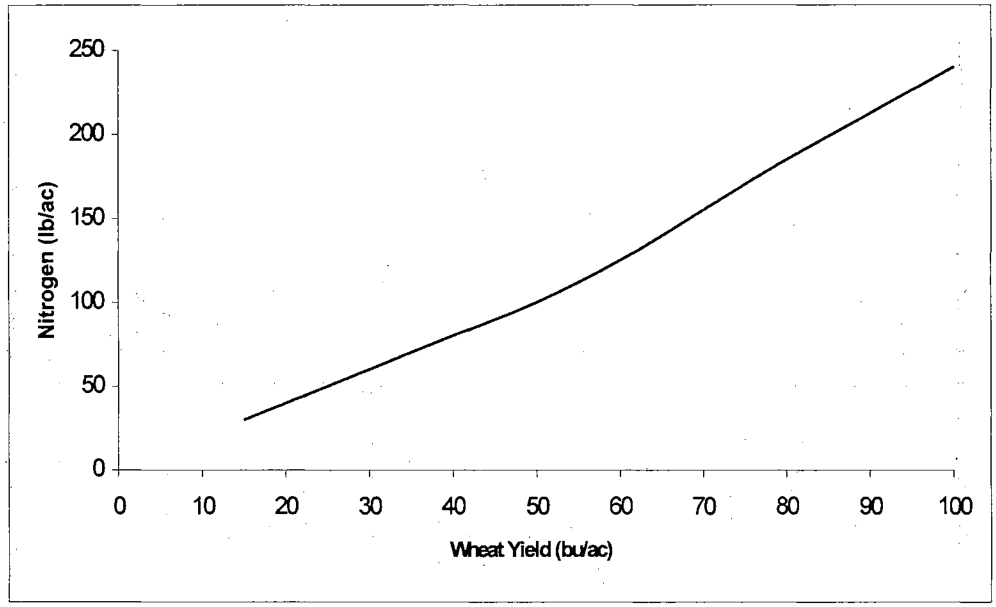

Figure 5: WHEAT YIELD-NITROGEN RESPONSE FUNCTION

APPENDIX - A
Oklahoma State University
Institutional Review Board

Protocol Expires: 5/19/01

Date : Friday, May 19, 2000

IRB Application No: AG0063

Proposal Title: ECONOMIC ANALYSIS OF SITE-SPECIFIC MANAGEMENT OF WHEAT CROP IN OKLAHOMA

Principal Investigator(s) :

John Solie	Mohammad Asim	Harry Mapp
521 Ag Hall	521 Ag Hall	321 Ag Hall
Stillwater, OK 74078	Stillwater, OK 74078	Stillwater, OK 74078

Reviewed and Processed as: Exempt

Approval Status Recommended by Reviewer(s) : Approved

Signature : Carol Olson

Carol Olson, Director of University Research Compliance

Friday, May 19, 2000
Date

Approvals are valid for one calendar year, after which time a request for continuation must be submitted. Any modifications to the research project approved by the IRB must be submitted for approval with the advisor's signature. The IRB office MUST be notified in writing when a project is complete. Approved projects are subject to monitoring by the IRB. Expedited and exempt projects may be reviewed by the full Institutional Review Board.

VITA

Mohammad Asim

Candidate for the Degree of

Doctor of Philosophy

Thesis: ECONOMICS OF WHEAT YIELD VARIABILITY FOR OKLAHOMA FARMERS USING SATELLITE IMAGES

Major Field: Agricultural Economics

Biographical:

Personal Data: Born in Peshawar, Pakistan, March 14, 1969, the son of Faqir Hussain and Rifat Ara.

Education: Graduated from St. Mary's High School, Peshawar, Pakistan, in 1984; received Fellow of Science Degree from Edwardes College, Peshawar, Pakistan, in 1986; received Bachelor of Science (Honors) Degree in Agriculture (major: agricultural economics) in 1990; received Master of Science Degree in Agricultural Economics from Oklahoma State University in 1997; completed requirements for the Doctor of Philosophy Degree at Oklahoma State University in December, 2000.

Professional Experience: Student Member of Dutch-assisted 'Project on Strengthening Planning and Development Department', Government of North-West Frontier Province, Pakistan, 1991-1992; Planning Officer, Provincial Agricultural Research Planning Directorate, Peshawar, Pakistan, 1992-1995; Graduate Research Assistant, Department of Agricultural Economics, Oklahoma State University, 1997-2000.