ECONOMIC STUDY OF ALTERNATIVE BEST MANAGEMENT PRACTICES FOR SWINE EFFLUENT APPLICATION TO CORN IN SEMIARID CLIMATE

By

RITA ISABEL RODRIGUES CARREIRA

Bachelor of Science in Economics
Universidade de Coimbra
Coimbra, Portugal
1996

Master of Science in Agricultural Economics
Oklahoma State University
Stillwater, Oklahoma
2000

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 2004

ECONOMIC STUDY OF ALTERNATIVE BEST MANAGEMENT PRACTICES FOR SWINE EFFLUENT APPLICATION TO CORN IN SEMIARID CLIMATE

Thesis Approved:

Dr. Arthur Stoecker
THESIS ADVISER

Dr. Francis Epplin

Dr. Jeffory Hattey

Dr. Michael Kizer

Dr. Bailey Norwood

Dr. A. Gordon Emslie
DEAN OF THE GRADUATE COLLEGE

ACKNOWLEDGMENTS

Education is what remains after one has forgotten everything he learned in school.

Albert Einstein

When I was working on finishing my master's degree I was very much aware of all the things I still did not know. So when Dr. Stoecker suggested that I pursue a doctoral degree, I saw that as an opportunity to learn a few more things and become more confident about all the knowledge that I had been accumulating throughout the years. As I near the completion of my doctoral degree, I realize that I still do not know many things and there is still much to be learned. But I also realize that my baggage of tools has increased significantly and I am better prepared to learn these things. Of course, to get to the point where I am at, I received support from a few people to whom I wish to express my gratitude.

I would like to thank my husband, Mark, for putting up with my occasional anxiety attacks, for having faith in my abilities, for pushing me to move forward, and for loving me. Working on my degree is a lot easier with him by my side. I would like to thank the Taliaferro family for taking me in and for their continuous support. My mother-in-law, Kathie, has become my second mother. I received, and still do receive, great amusement and joy from the little Taliaferro members, who are my wonderful nephew and nieces, especially Sophia and Baby Riley. Over the last three years, a lot of my inspiration has come from my nephew Rodrigo, who I always carry in my thoughts and heart. Of course I am indebted to my parents, who have shown me right from wrong.

Being a student in the Department of Agricultural Economics at OSU has been a wonderful experience. Since I became a student here, I have been nurtured by faculty, staff, and students. I think they do too good of a job, as it is quite difficult to leave such a protective environment—maybe that is why it takes me such a long time to finish my degrees.

I would like to mention a few of the professors who have helped and taught me the most: my adviser Dr. Arthur Stoecker, who still thinks I'm a smart kid; Dr. Francis Epplin for his impeccable teaching; Dr. Wade Brorsen, who showed me how to think outside the box; and Dr. Chanjin Chung for his incessant dedication to us, students. I thoroughly enjoyed learning from and working with them and I am thankful for all their time and effort devoted to my success. When I decided to relearn Statistics I was fortunate to take classes with some of the best Statistics professors I have met. I cannot forget Dr. Jeanne Hill for being an amazing educator and friend; Dr. Christopher Bilder for opening the doors to the SAS world; and Dr. Joshua Tebbs for making a lot of things make sense, finally.

Some of the Agricultural Economics staff members I would like to thank are Ms. Anna Whitney for becoming a friend and for being on top of things; Ms. Joyce Grizzle for her concern and support; Ms. Gracie Teague and Mr. Andrew Lowry for rescuing me from computer evil and showing me neat things; and Mrs. Harris for providing me with laughter and wisdom. I must also thank Mr. Tim Huff from ISS for showing me how to implement my dreams.

I also am appreciative of the following people, who were or are students in this department: Ms. Heather Greer, for making it sound easy; Ms. Francisca Richter for inspiration and support; Ms. Larysa Rybak for continuously pushing me and for asking me questions; Ms. Joni Wait-Klumpp for good laughs and for asking me more questions; Mr. Robert Hogan for being such a good example; and Mr. Seong-Huyk Hwang, my Statistics homework buddy, for his kindness and intelligence.

I am grateful for having received funding from a Sitlington Scholarship and from a Spielman scholarship, during my doctoral program. I was also honored with the Dr. Pepper bottle, which I eagerly look forward to pass along. I am indebted to Dr. H.L. Goodwin for all his support and understanding during the last stages of my doctoral program.

As I finish up, I think about all that has happened since I became a student. I never imagined being where I am today. Either I am one very lucky person or someone up there has been working hard on my behalf. The latter must be true. Agradeço-te Haziel por tudo.

Namaste!

TABLE OF CONTENTS

CHAPTER PAGE

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

NOMENCLATURE

BMP	Best management practice
CAFO	Concentrated Animal Feeding Operation
CONOPT	Large-scale nonlinear optimization solver in GAMS
CPS	Center pivot sprinkler irrigation system
CWA	Clean Water Act
EPIC	Erosion Prediction Impact Calculator
EQUIP	Environmental Quality Incentives Program
ERS	Economic Research Service
FACT	Food, Agriculture, Conservation and Trade Act (1985)
FAIR	Federal Agriculture Improvement and Reform Act (1996)
GAMS	General Algebraic Modeling System
gpm	Gallons per minute
GRG	Generalized Reduced Gradient
ha	Hectare
kg	Kilogram
KSU	Kansas State University
M-B	Mitscherlich-Baule
MINOS5	Optimization algorithm in GAMS
mt	Metric ton

NCDC	National Climatic Data Center
NH_3	Ammonia
NH_4^+	Inorganic or mineral form of nitrogen called ammonium
NLMIXED	Nonlinear mixed procedure in SAS
NLP	Nonlinear programming
NO_3^-	Inorganic or mineral form of nitrogen called nitrate
NOAA	National Oceanographic and Atmospheric Agency
NUE	Nitrogen use efficiency
OSU	Oklahoma State University
PDF	Probability density function
QS	Quarter section
SAS	Statistical Analysis Software
SDI	Subsurface drip irrigation
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VBA	Visual Basic for Applications

MODEL VARIABLES AND PARAMETERS

NPV	Net present value (\$/ha)
θ	Percentage of land under irrigation (%)
P^c	Price of corn (\$)
Y_t	Corn yield per hectare in year *t* (metric tons/ha)
C^e	Per unit cost of effluent (\$/Kg)
F_t	Effluent applied in year *t* (Kg/ha)
U_t	Amount of urea applied in year *t* (Kg/ha)
C^m	Maximum unit cost of pumping water from aquifer (\$/m^3)
C^w	Unit value of water extracted (\$/m^3)
W_t	Amount of water in aquifer (m^3/ha)
G_t	Amount of water extracted from aquifer (m^3/ha)
OVC	Other variable costs (\$/ha)
C^{IS}	Installation costs of irrigation system (\$/ha)
r	Discount rate
$\bar{Q}$	Lifetime of irrigation system
R^w	Net revenue of dry land wheat (\$/ha)
σ_N	Proportion of nitrogen in effluent
σ_P	Proportion of phosphorus in effluent

N_t	Amount of nitrogen in effluent (Kg/ha)
P_t	Amount of phosphorus in effluent (Kg/ha)
$\eta_{01},...,\eta_3$	Parameters of yield function
D	Irrigation system dummy variable, takes value 1 for SDI, 0 otherwise
SN_t	Amount of soil nitrogen in year *t*
SP_t	Amount of soil phosphorus in year *t*
ε_t	Yield function error term, $\varepsilon_t \sim N\left(0, \exp\left(\alpha_0 + \alpha_1 G_t\right)\right)$
$\lambda_0,...,\lambda_6$	Parameters of soil nitrogen carryover equation
ϑ_t	Soil nitrogen equation error term, $\vartheta_t \sim N\left(0, \exp\left(\phi_0 + \phi_1 G_t + \phi_2 N_t\right)\right)$
K_t	Nitrogen percolation in soil in time period *t* (Kg/ha)
V_t	Ammonia volatilization in soil in time period *t*
$\delta_0,...,\delta_3$	Parameters of soil phosphorus carryover
ϖ_t	Error term of soil phosphorus carryover, $\varpi_t \sim N\left(0, \exp\left(\kappa_0 + \kappa_1 G_t + \kappa_2 P_t\right)\right)$
$\gamma_0,...,\gamma_6$	Parameters of nitrogen percolation equation
ξ_t	Error term of nitrogen percolation equation, $\xi_t \sim N\left(0, \exp\left(\varphi_0 + \varphi_1 G_t\right)\right)$
ψ	Coefficient of relative risk aversion in power utility function
Ω	Initial producer wealth assumed in stochastic model

CHAPTER I

INTRODUCTION

Background

The main crop products of Texas County, Oklahoma, are sorghum, wheat, hay, and corn. The county is one of the highest concentrated animal production areas in the United States. The 2002 Agricultural Census reported that this county's hog and pigs inventory was 1,073,134 animals, while the number of hogs and pigs sold annually was 2,081,878 animals; this amounts to almost $194.5 million. The expansion of large swine concentrated animal feeding operations (CAFOs) in the county started in 1991 after the Oklahoma Senate passed bill 518, which eased restrictions against corporate farming. The abundance of corn and sorghum, which are important feeding inputs for the swine industry, also attracted large swine corporations to the area. A dramatic increase in the hog and pig population in Texas County occurred in a 10-year period (Table 1).

Table 1. Millions of Hogs and Pigs at the National, State and County Levels (Source: 2002 and 1997 Census of Agriculture)

	1992	2002	Change
United States	57.56	60.4	4.9%
Oklahoma	0.26	2.25	765%
Texas County, OK	0.013	1.07	8,130%

The installation of large CAFOs brought new economic life to the Oklahoma Panhandle region but after a few years in operation, the population expressed its discontentment and apprehension over the management of animal wastes (Branstetter, 1997). Reports of improper animal waste management in popular media became frequent and the situation rose to a state concern, which culminated in March of 1998, when the Oklahoma legislature imposed a moratorium on construction and expansion of hog farms in Oklahoma. The moratorium was lifted later in the year by Senate Bill 1175, which many considered introduced the most restrictive hog production regulations in the United States (Hinton, M. 1998).

The main environmental problems associated with swine waste management and application to soil are potential phosphorus accumulation in the soil, which in some areas may come in contact with surface water, via water and/or soil erosion, leading to eutrophication problems; nitrogen leaching in the soil which may contaminate underground water in wells and aquifers; increased salinity of soil which may hinder the quality of the soil for future agricultural use; and nitrogen volatilization as ammonia, which pollutes the atmosphere and is a source of offending odors that displease the population. There is also the potential for treatment lagoons or storage ponds to overflow especially during extreme precipitation events. The threat level of these situations is not very great in a semiarid region as the one this study focuses on, but none of these situations is impossible and they become serious issues if swine manure is mismanaged.

Animal manure is an asset to farmers (Zhang and Hamilton, 2002; Zhang, 2003), but proper management of animal manures is expensive and labor intensive. Serious logistic problems also can occur in regions where water is not readily available, as many management systems are also very water demanding. The Oklahoma Panhandle has a temporally limited supply of water resources and underground water must be allocated not only between present and future use, but also between present alternative uses such as animal production, irrigation, and human consumption. It is imperative that proper animal waste management practices be developed and their economic feasibility assessed to assist farmers and policy makers in making wise decisions in water management and environmental protection for the region.

Stichler and McFarland (2001) say that the most limiting factor for crop production in Texas is water availability. The same can be said of Oklahoma, particularly Texas County. In Texas County, surface water is scarce and rainfall is inadequate. Most of the water used in crop and animal production is extracted from the Ogallala aquifer—a formation that is saturated with water, which was deposited 10 million years ago. The recharge of the aquifer is negligible compared to the extraction rate and groundwater use in the area can be viewed as a mining activity (Stoecker, Seidman, and Lloyd, 1985). In an aquifer, fresh groundwater floats over salt water. Over long periods of groundwater extraction, water quality declines as the stock of fresh groundwater drops and the producer gets closer to the salt water supply, which is not suitable for most irrigated crops. Although, current aquifer saturation thickness varies between 100 and more than 400 feet, eventually, the fresh water in the aquifer will be too limited and/or deep to be extracted profitably. Economic exhaustion will be achieved when “net returns per acre from dry land farming exceed net returns per acre from irrigation” (Harris, Mapp, and Stone, 1983, p. 3). Animal production and crop production compete for the use of the limited water resources. Recycling the water and the nutrients in the manure by applying it to crops constitutes an asset to agricultural production. The combination of water recycling and irrigation methods that are more water efficient help prolong aquifer life; but inadequate nutrient management poses an environmental risk that the nutrients (mainly nitrogen and phosphorus) from the manure might contaminate surface and underground waters.

Animal producers in Texas County face stringent legal and economic constraints in the management and disposal of the manure produced in large concentrated swine facilities. It is well known that part of the nitrogen in manure, if ill managed, tends to volatilize to the atmosphere in the form of ammonia, which reduces the value of the manure to the farmer and may pollute the environment. On the other hand, if manure is applied under the wrong atmospheric conditions, nitrogen can also leach through the soil and contaminate underground waters. Although manure management issues have been actively studied in recent years, best management practices (BMPs) regarding the effect of time of application and method of land application of swine manure on the crop's nutrient utilization have not been fully developed for Texas County.

The management of phosphorus content in manure also poses serious problems. Albeit plants need nitrogen and phosphorus, the nitrogen-phosphorus ratio requirement of plants is higher than what is supplied in the manure. Current chemical analyses show that the soil in Texas County is not phosphorus saturated (Zhang, 2002), but there are studies that show that even phosphorus deficient soils may become phosphorus saturated when they receive animal manure over a long period (Sharpley et al., 1991). Thus, continuous land application of swine manure may be linked to phosphorus accumulation in the soil, which may lead to eutrophication of nearby surface waters due to the action of wind and water erosion. Hence, choosing a crop that is economically feasible and that adequately utilizes phosphorus as a nutrient, thus favoring this nutrient's removal from the soil, is of essential interest to farmers and society. The attractiveness of this crop to farmers depends primarily on economic aspects, but environmental issues must also be taken into account.

Geographic and Historic Considerations

The absence of a great body of surface water in the High Plains of the United States causes temperatures to reach extreme low cold in the winter and intense heat in the summer (Kromm, D. E. and S. E. White. 1992a). Although surface water is lacking, the High Plains region is rich in groundwater, as it overlies the High Plains aquifer—a formation composed of several aquifers, extending 174,000 square miles, and underlying eight states: South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Texas and Oklahoma. The most important aquifer is the Ogallala aquifer, which accounts for 134,000 square miles of the High Plains aquifer. Ogallala aquifer refers to the water saturated part of the Ogallala formation, which was created when the Rocky Mountains were uplifted by tectonic forces, some 10 million years ago.

Contrary to the romanticized beliefs of early American settlers, who viewed the aquifer as an inexhaustible, flowing underground river, the Ogallala receives little recharge (Kromm and White 1992a, p.16). Between 1930 and 1990, roughly 11 percent of the aquifer's reserves were used up; it is projected that by 2020, 25 percent of the reserves will have been completely utilized (Lewis, 1990). Given current extraction rates, depletion is inevitable. Kromm and White (ibid.) use four main ideas to address aquifer depletion: saturated thickness, groundwater recharge, groundwater flow, and depth to water table. The saturated thickness (vertical distance between the water table and the base of the aquifer) of the Ogallala aquifer varies greatly from less than 50 feet in certain parts of Texas and New Mexico, for example, to more than 1000 feet in part of Nebraska (Figure 1). The recharge of the aquifer, through mainly rainfall, is negligible for most of the aquifer given the high evapotranspiration rates of the High Plains. On average, groundwater flows one foot per day from west to east, amounting to merely 6.91 miles in 100 years.

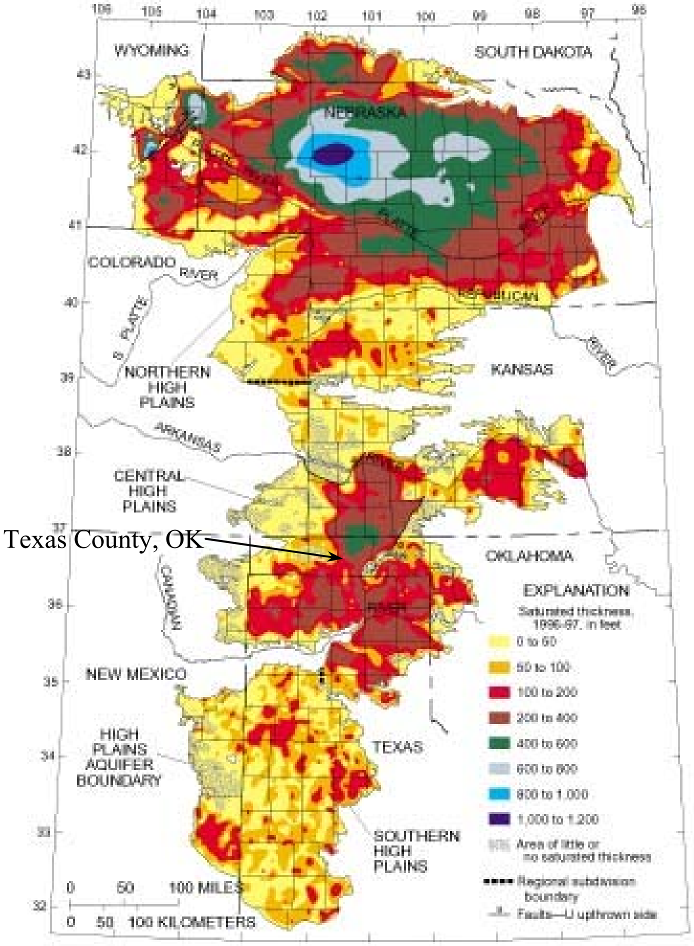


Figure 1. Map Illustrating Feet of Saturated Thickness of High Plains Aquifer for the 1995-1997 Period, as Published in Peterson, Marsh, and Williams (2003)

The depth from the surface to the water table greatly affects the economic feasibility of extracting water from the aquifer, since the farther down you need to dig to reach the water table, the more energy you must spend to lift the water. Depth to water table varies greatly across the aquifer. In certain areas of Texas it can be greater than 300 feet and in parts of Nebraska, it can be less than 50 feet.

Despite the climatological volatility of the High Plains of the United States, the region offers excellent conditions for agricultural production due to the presence of irrigation, a rich mollisol soil, abundant sunshine, low relative humidity, and tendency toward cool evenings in the summer (Kromm and White, 1992a; Chapelle, 1997). The crucial element of the agricultural success of the High Plains is the presence of groundwater irrigation.

Following World War II, irrigation technology became affordable, center pivot irrigation was introduced, and the irrigated acreage in the High Plains expanded considerably. Higher yields of corn, sorghum, alfalfa, and other irrigated crops initially increased producers' revenues but the decline in agricultural crop prices that ensued captured much of the monetary benefit of the increased productivity. However, the lower crop prices were decisive for the expansion of animal production in the High Plains (Chapelle, 1997).

The High Plains region became one of the most productive agricultural regions in the world. By mid-1970s, when the world economy was still in shock because of the oil crisis, and the United States faced economic, social, and political difficulties, the yields of many wells in Texas and New Mexico had been reduced dramatically; some wells even dried up. American authorities were confronted with the bitter truth—the recharge of the aquifer was insignificant compared to the extraction rate, leading to what some media called the "mining of a nonrenewable resource" (Kromm and White, 1992b). Pumping of the Ogallala steadily and irreversibly reduced the aquifer's saturated thickness (Peterson, Marsh, Williams, 2003).

The 1980s brought about a mix of good and bad news for High Plains' producers. In the areas where the water table had declined, water quality deteriorated due to higher dissolved solids concentration and agricultural pollution from pesticides, herbicides, and fertilizers (Kromm and White, 1992b). These problems were not exclusive to the High Plains, as many aquifers across the United States suffered and continue to suffer this malady. On a positive note, technological developments increased the water use efficiency of center pivot irrigation, which extended the irrigation horizon for many producers. It was found that the recharge of the aquifer was greater than what had been predicted and along the Platte River in Nebraska, aquifer water levels actually increased (Chapelle, 1997).

Texas County, located in the Oklahoma Panhandle, which is part of the High Plains, has a semiarid climate and it is common for years of drought to be followed by several years of above normal rainfall. Morphologically, the region consists of gently undulating upland planes and eroded, rough breaks and narrow flood plains along streams (USDA, Soil Conservation Service, 1961). The county overlies the Ogallala aquifer in such a way that saturated thickness ranges from 0 to more than 400 feet (Figure 1).

Table 2. Selected Texas County Agricultural Statistics (Source: 1997 and 2002 Census of Agriculture)

	1992	1997	2002
Number of farms	704	785	1,002
Land in farms (acres)	1,051,384	1,086,667	1,181,025
Average size of farm (acres)	1493	1384	1179
Total cropland (farms)	571	653	786
Total cropland(acres)	621,821	631,680	697,744
Total harvested cropland (farms)	491	432	319
Total harvested cropland (acres)	347,527	362,775	276,672
Irrigated land (farms)	257	217	190
Irrigated land (acres)	160,604	137,898	161,569
Average irrigated land per farm	625	635	850

On April 4, 1996 significant changes occurred in the American agriculture legal framework with the passage of the Federal Agriculture Improvement and Reform (FAIR) Act. One of the greatest differences between the FAIR Act and its precursor, the 1990-amended Food, Agriculture, Conservation and Trade (FACT) Act (originally passed in 1985), was the removal of the link between income support payments and farm prices, thus eliminating deficiency payments which took place when average farm prices fell below the target price. According to the FAIR Act, a farmer who, in any one of the five years prior to 1996, had participated in the wheat, feed grains, cotton, and rice programs, was eligible to receive payments and loans on program commodities if he entered a "production flexibility contract" covering the 1996-2002 period. The contract affected several aspects of the farmer's activity such as (i) participants had to "continue to maintain conservation plans including compliance with highly erodible land conservation provisions and wetland conservation provisions." (ii) Participants could continue to voluntarily participate in the Conservation Reserve Program (CRP), a provision of the original FACT Act which allowed landowners to receive government payments in exchange for removal from production[1] of highly sensitive land for a period of 10 to 15 years; the maximum cumulative CRP area was reduced from 38 million acres in 1990 to 36.4 million acres. (iii) Participants could also receive funding via the Environmental Quality Incentives Program designed to maximize environmental benefits per dollar spent and which replaced the Water Quality Incentives Program and the Environmental Easement Program (ERS/USDA, 1996).

Between 1992 and 2002, the number of farms using irrigation in the county dropped from 257 to 190 (Table 2) and irrigated acreage increased approximately 1,100 acres during this period (although a significant decline took place between 1992 and 1997). This corresponds to a 26 percent decline in the number of farms using irrigation and a 0.6 percent increase in the number of acres irrigated (Table 3), the number of irrigated acres per farm between 1997 and 2002 was over 850, a 36 percent increase over the per farm irrigated acreage in 1992.

Table 3. Percentage Change in Selected Texas County Agricultural Statistics (Source: 2002 and 1997 Census of Agriculture)

	1992-2002	1992-1997	1997-2002
Number of farms	42.33%	11.51%	27.64%
Land in farms	12.33%	3.36%	8.68%
Total cropland (farms)	37.65%	14.36%	20.37%
Total cropland(acres)	12.21%	1.59%	10.46%
Total harvested cropland (farms)	-35.03%	-12.02%	-26.16%
Total harvested cropland (acres)	-20.39%	4.39%	-23.73%
Irrigated land (farms)	-26.07%	-15.56%	-12.44%
Irrigated land (acres)	0.60%	-14.14%	17.17%

---

[1] Originally, the 1985 FACT Act allowed a maximum area of 45 million acres of land to be enrolled in the CRP.

The overall number of farms harvesting cropland declined 35.03 percent from 1992 to 2002, but in terms of harvested acreage, the decline was only 20.39 percent, indicating that some sort of concentration of cropland took place. For the same period, the number of farms in the county increased 42.33 percent, while acreage in farming only increased 12.33 percent, which could indicate a tendency toward smaller farms, a possible consequence of the CRP provision changes mentioned above.

Problem

Current irrigation methods practiced in the county include furrow irrigation and sprinkler irrigation, none of which is very water efficient (O'Brien, Dumler, and Rogers, 2001). While furrow irrigation does not pose great concerns in terms of water evaporation as sprinkler irrigation does, it does not promote uniformity of water and nutrient application to the field, thus some plants might receive too much water and nutrients while others may be lacking. Some forms of sprinkler irrigation also pose drawbacks such as high rates of water evaporation; when applying swine effluent with a center pivot sprinkler the main concern is ammonia volatilization. These two facts imply that valuable resources, water and nitrogen, are being lost to the atmosphere instead of being available to the crop. If the amount of water mixed with effluent applied and the pressure used to apply it are great enough to break the top layer of the soil and move soil particles considerably, soil erosion and phosphorus runoff may become a problem.

Phene and Phene (1987) contend that drip irrigation, a technique developed in Israel in 1964, has advantages over the current irrigation methods in terms of water and energy conservation, crop yields, and better crop quality due to better water management and greater management flexibility. In the case of swine manure effluent application, drip irrigation also allows for less ammonia volatilization, virtually eliminates the risk of phosphorus runoff, and ensures greater uniformity of nutrient and water application to crops than present irrigation techniques.

Given all these advantages of drip irrigation, one would assume that this technology would be much more commonly adopted in water constrained regions than what it has been. The adoption of SDI faces obstacles such as higher installation costs, higher risk of system failure, more labor-intensive maintenance, and shorter system life compared to center pivot irrigation. The main difficulty in its adoption is the high installation cost (Martin, 2003). Presently, farmers can receive a monetary incentive from the Environmental Quality Incentives Program, EQIP, to adopt water-efficient irrigation systems. As introduced in the FAIR Act, the EQIP was authorized at $1.3 billion in mandatory spending over 7 years; besides the monetary component, the EQIP also provides technical and educational assistance. One of the biggest priorities in the allocation of funds was environmental concerns connected with livestock production, which received at least half of the funding. In terms of an individual farmer, producer payments could not exceed $10,000 in any one fiscal year or $50,000 for a multiyear contract (ERS/USDA, 1996). In 2002, EQIP reimbursed up to 50 percent of the SDI system cost. In 2003, the incentive was modified to $125 per acre. In return, farmers must sign an agreement requiring a net water savings over a certain time period. In some cases, the agreement may require part of the land to be set aside as dry land (Martin, 2003).

Kansas State University has researched extensively the use of subsurface drip irrigation and how this system compares with center pivot sprinkler irrigation in terms of efficiency and monetary benefits. Certain aspects of the problem, such as weather volatility and constrained irrigation water supply, still need to be addressed.

Currently, best management practices for drip irrigation using swine effluent are being developed for Texas County. If one considers decision dynamics, and the inherent risks of farming under these conditions, the conclusions achieved with static analysis may shift. The long-term consequences for groundwater, nitrogen accumulation in soil, and phosphorus accumulation in soil, of using drip irrigation versus center pivot irrigation, in conjunction with swine effluent, and taking into account dynamic optimization, have not been addressed by present literature. A long term economic analysis of drip irrigation versus center pivot irrigation, taking into account decision dynamics and producer behavior, is lacking in present literature.

Objectives, Hypotheses, and Significance of the Study

Objectives

The objective of this study is to improve available economic information regarding swine manure management, groundwater management, and irrigation practices in corn production for the semiarid Oklahoma Panhandle over a long-term production horizon. Specifically this study will

1. Evaluate how profitable SDI is compared to center pivot sprinkler irrigation, given a virtually non-renewable water supply and effluent application to

irrigated corn in a semi-arid setting over a long-term production horizon of 100 years, assuming a risk neutral producer.

2. Determine the effects of optimal management of both irrigation systems on length of aquifer life, decline in water table, cumulative corn yield, soil phosphorus carryover, soil nitrogen carryover, nitrogen percolation, and expected net revenues over the production horizon.
3. Assess how sensitive the optimal solution is to 1) a change in the initial level of the water table, 2) an increase in the real discount rate, 3) an increase in the price of natural gas.
4. Ascertain the effect of risk-aversion behavior on the profitability of both irrigation systems.

Hypotheses

The hypotheses underlying this study are

1. For long planning horizons, such as the 100 years assumed for this study, SDI becomes economically more attractive comparatively to center pivot irrigation, given a nonrenewable water supply.
2. SDI allows for less long-term phosphorus accumulation in the soil and conserves more soil nitrogen than center pivot irrigation.
3. Cumulative corn yield over time should be higher with SDI, since higher water efficiency allows a greater area to be irrigated over time.
4. When considering the uncertainty of nitrogen application (from effluent) rates due to ammonia volatilization, and long-term groundwater allocation,

subsurface drip irrigation is economically more profitable than center pivot sprinkler irrigation.

Significance of Study

This study innovatively uses a stochastic dynamic programming analysis to compare the effect of managing weather uncertainty using alternative irrigation practices on the expected net returns of the farmer. Many studies have been conducted on the merits and demerits of subsurface drip water irrigation and center pivot irrigation and fertilizer/manure application. Most of these studies present the economic analysis and the monetary implications for the producer of both systems. However, current literature many times adopts deterministic and/or static analysis methods and does not pursue other research venues, such as dynamic programming or stochastic dynamic programming methods, which can improve upon current research. Although these methods are more cumbersome, they are useful because they provide producers with long term implications of their actions. In the case of stochastic dynamic analysis methods, risk analysis of alternative scenarios can be studied and producer actions which maximize expected long run returns can be identified. Developments in computer hardware and software, as well as more available weather data, have made these methods easier to implement in the treatment of the present problem.

Study Site Assumptions and Data Sources

Study Site Assumptions

Data used in this study refer to Texas County, located in the semiarid Oklahoma Panhandle. For the period 1994-1999, in Texas county, the median value of soil test P index was 59 and the median value of soil pH was 7.5 (Zhang 2002). Almost all of Texas County overlies the High Plains Aquifer. It was assumed the area to be irrigated was a quarter section of land with the characteristics of an average Oklahoma Panhandle farm: Richfield soil, relatively flat, and dependent on groundwater for irrigation. It was assumed that the farm overlies the Ogallala aquifer, such that the distance to the bottom of the aquifer was 114.3 m, the aquifer saturated area was 36.58 m deep, porosity was about 50%, and aquifer specific yield was 15%. At the beginning of the study, there were 21.9 m of water available for each hectare of irrigated area. The ratio of irrigated area to extraction area was assumed to be 20%.

It was assumed that the farm's well was located in the center of one of the sides of the quarter section and that its capacity was 1000 gpm. The farm was assumed to produce irrigated corn. The production area using SDI was approximately 63 ha. Under irrigation with a center pivot sprinkler system it was assumed approximately 51 ha were cultivated with corn and the remaining area of the quarter section was cultivated in dry land wheat-fallow rotation. The farm also included three quarter sections which were cultivated in dry land wheat-fallow rotation. For the context of this study, irrigation uses a mixture of swine effluent and fresh groundwater.

Data Sources

Due to data unavailability, irrigated corn yields were simulated in EPIC (Erosion Prediction Impact Calculator) for multiple years, taking into account the statistical distributions of climatological variables in Texas County, Oklahoma. Daily weather data for the Goodwell Research Station were obtained from the National Climatic Data Center (NDC, a unit of NOAA) and the Oklahoma Climatological Survey referring to the 1948-2002 period. When data were unavailable for the Goodwell Research Station, approximate data were computed by interpolating available data collected for the research stations of Amarillo (Texas), Garden City (Kansas), and Dodge City (Kansas). Additional weather data were obtained from the Oklahoma Mesonet, beginning in 1994. Monthly averages of the Goodwell data were computed in SAS and Excel to be used as weather probability distributions input for the EPIC simulations. These statistics are reported in Table 4. The conditional probabilities were computed by defining event D as a "dry day" and event W as a "wet day." In a two-day period, the possible outcomes are (D,D), (D,W), (W,D), and (W,W). The joint event probabilities were computed as well as the probability of a dry day and the probability of a wet day. The conditional probabilities are then a straight-forward application of the definition of conditional probability; for example, the probability of a wet day given a dry day is

$$\Pr\left(W \mid D\right) = \Pr\left(W, D\right) / \Pr\left(D\right). \tag{1}$$

Data were simulated for different weather patterns which were randomly sampled from these distributions. Groundwater use, availability, and water quality data were obtained from the USGS and Underground Water Conservation Districts. Crop prices and production cost information were obtained from USDA publications, irrigation catalogs, irrigation system suppliers, and extension publications from Oklahoma State University and Kansas State University.

The subsurface drip irrigation system was designed in conjunction with Dr. Michael Kizer, a Biosystems and Agricultural Engineering professor who specializes in irrigation. Additional design information was obtained from previous literature (Lamm, Rogers, Alam, and Clark, 2003; Rogers, Lamm, and Alam, 2003; James, 1988; Scherer, Kranz, Pfost, Werner, Wright, and Yonts, 1999; Sorensen, Wright, and Butts, 2001; Phene and Phene, 1987), irrigation catalogs (Dripworks, Schumacher Irrigation), and Internet websites (http://www.dripirrigation.com, http://www.dripirr.com). The subsurface drip irrigation system design can be viewed in Appendix A. The cost for the SDI system installation in a quarter section of land is $1,703.30/ha. The budget for the SDI system can be viewed in Appendix B.

The center pivot system assumed for this study followed closely the specifications of O’Brien, Dumler, and Rogers (2001). Several irrigation firms were contacted in an attempt to obtain a current cost estimate for the center pivot system, but no reply was attained. Thus, the estimated cost of the system provided in O’Brien, Dumler, and Rogers was updated to reflect 2003 costs. The updated cost for this system installation in a quarter section of land is $946.76/ha. The updated budget for the center pivot system can be viewed in Appendix C.

Table 4.Monthly Average Weather Characteristics for Goodwell Research Station for 1948-2002 Period and Used as Weather Generating Data in EPIC (Source: National Climatic Data Center, Oklahoma Mesonet, Oklahoma Climatological Survey)

Variable\Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Average maximum air temperature, ^{o}C	8.20	11.30	15.71	21.56	26.12	31.59	34.09	32.12	28.88	23.05	14.54	8.98
Average minimum air temperature, ^{o}C	-7.42	-5.22	-1.72	4.06	9.69	15.26	18.04	16.51	12.43	5.59	-1.74	-6.21
Std. deviation maximum air temperature, ^{o}C	9.45	9.08	7.99	6.63	5.92	4.98	3.78	7.85	5.65	6.49	8.34	9.02
Std. deviation minimum air temperature, ^{o}C	5.73	5.49	5.13	4.59	4.05	3.46	2.43	5.30	4.27	4.62	5.22	5.30
Average precipitation, mm	6.6	10.0	24.0	29.5	68.6	62.1	71.5	59.5	39.5	28.7	13.3	8.3
Std. deviation of daily precipitation, mm	3.3	4.9	6.7	8.7	12.6	10.4	11.7	12.0	11.6	10.6	6.2	3.8
Skewness for daily precipitation	2.60	3.11	2.36	2.03	2.99	2.66	2.18	2.56	2.77	2.49	2.09	1.92
Probability of a wet day after a dry day	0.070	0.081	0.102	0.110	0.187	0.204	0.199	0.175	0.143	0.085	0.072	0.066
Probability of a wet day after a wet day	0.314	0.313	0.351	0.346	0.436	0.399	0.352	0.361	0.344	0.374	0.294	0.295
Average number of rain days per month	2.87	2.98	4.18	4.33	7.65	7.64	7.27	6.69	5.38	3.71	2.80	2.60

CHAPTER II

LITERATURE REVIEW

Groundwater Issues

As early as the 1960s, population and authorities were aware that the High Plains aquifer was a finite resource. In the 1970s, these concerns materialized as many wells dried up in southern states. Much of the recent literature on the High Plains Aquifer addresses the issue of equity in exploiting the water resources of the aquifer. Two types of equity have been referenced: equity within a generation of users, or fairness, and equity across different generations of users, or sustainability (Peterson, Marsh, and Williams, 2003). Fairness is closely related to water conservation as one well's water yield affects the yield of nearby wells. The necessity of conserving water is closely related to the fact that the aquifer base is not flat, which implies that aquifer water will become unavailable at different times in different locations—wells above deep parts of the aquifer will yield water long after neighboring wells located on shallower parts of the aquifer have dried up (ibid.).

Kromm and White, in 1992, addressed sustainability by reflecting on the conflict of interests between present and future generations in the groundwater use of the High Plains Aquifer as follows:

> Ironically, while our nation's farmers are confronting agricultural surpluses, low crop prices, reduced land values, and foreclosures, we are

> systematically mining a virtually nonrenewable resource to produce more in a time of plenty. At the national scale it might seem prudent to conserve High Plains groundwater for future generations, but at the individual or local level, irrigated agriculture is often perceived as necessary for survival. (Kromm and White, 1992b, p. 60)

The acuteness of the inter-temporal conflict cannot be diminished but the point in time at which aquifer exhaustion will occur can be postponed by adopting more efficient irrigation techniques, water recycling practices, and adequate crop selection. Economic analysis of groundwater exploitation, given optimal resource allocation and irrigation management, shows that the economic exhaustion may occur before the physical exhaustion of the aquifer (Stoecker, Seidmann, and Lloyd, 1985) thus water conservation can be an optimal economic result. It may make sense to favor present aquifer water use over future use if the net present value of present consumption outweighs the net present value of future consumption (ibid.).

A discussion of fairness and sustainability cannot be complete without addressing the legal framework regulating groundwater use. At the federal level, groundwater is unregulated except when it affects interstate diversion and interstate commerce.[2] Regulation of groundwater use is deferred to the states. Groundwater laws implemented by each state are very different, which is a source of conflict in the case of common resources such as the Ogallala Aquifer.[3]

The use of groundwater in Texas County obeys the Oklahoma groundwater legal framework, implemented in 1972, which many consider to be the most equitable of any High Plains states (Aiken cited in Templer, 1992). The state of Oklahoma recognizes

---

[2] The Clean Water Act (CWA) is only applicable to “navigable waters,” and not groundwater.

[3] For a detailed description of the different legal frameworks of the states that overlay the High Plains Aquifer, see Templer, 1992.

that the Ogallala aquifer will be eventually exhausted. Access to groundwater is regulated via a permit system, which assures a minimum aquifer life of 20 years. Groundwater uses are not prioritized; instead the Oklahoma Supreme Court upheld, in 1978, that all beneficial water uses share the same priority. This framework ensures an "orderly exhaustion" of groundwater resources.

Subsurface Drip Irrigation

Microirrigation is an irrigation technique term referring to any low volume application of water to the soil whether by drip, trickle, or micro-sprinkler systems (Cuykendall and White, 1998). Camp (1998) notes that the term subsurface drip irrigation has had different connotations over time, being that some definitions of SDI are more stringent than others with respect to the depth of placement of the laterals. Many people confused SDI with subirrigation, a method in which the water table is raised to within or near the root zone (ibid.). Since mid-1980s, the term subsurface drip irrigation has been associated consistently with "drip/trickle application equipment installed below the soil surface" (ibid.).

A survey of apple producers in New York State who used microirrigation technology indicated that although producers had better results with drip irrigation, they were unable to quantify their costs and benefits of microirrigation (Cuykendall and White, 1998). To study the economic implications of drip irrigation in apple orchards in New York, Cuykendall and White performed a cost-benefit analysis of two drip irrigation systems—using 15 mil tape (the lifespan of this investment is 7 years and costs

$464/acre, assuming 10 acres) and pressure compensating tubing (lifespan of 15 years, $794/acre assuming investment on 10 acres). The authors concluded that investment in drip irrigation using tubing or tape is profitable for apple orchards in New York State. A subsequent study of Cuykendall et al. (1999) evaluated the economic consequences of drip irrigation in juice grape vineyards in New York State and obtained similar results to the apple orchard study.

U-Kosaramig evaluated the use of SDI to apply dairy wastewater to alfalfa in California. The experiment used dairy wastewater as the only source of nutrients for alfalfa, which was harvested once a month. Yields were found to be relatively high compared to most commercial fertilizers. Over two years of operation, the SDI system worked correctly and did not have any plugging problems. The author concluded that irrigation efficiency could be improved by carefully programming the SDI system.

The effect of long-term swine manure land application was studied by Sharpley et al. for Delaware County, located in the Eastern Oklahoma. The eastern region of Oklahoma faces humid climate and has several watersheds; these are conditions that combined, pose serious risks of phosphorus runoff from manure treated soil. Sharpley et al. (1991)found that there was “no consistent effect of waste application on soil physical properties” (Sharpley et al., p. 9) but the phosphorus content was greater in treated soil as expected. The scarcity of surface waters in Texas County makes it even more important to study alternative practices for swine manure management that protect the existent water streams.

For the last 15 years, Kansas State University has been conducting research on corn production using SDI with the purpose of enhancing water conservation, protecting water quality, and developing appropriate SDI technologies for the Great Plains region. They found that the system when using freshwater can be economically feasible in the area and that it is possible to extend the SDI system life from 10-15 years to 20-25 years, using careful management. Research was also conducted to evaluate the economic feasibility of using the SDI system with beef lagoon effluent. This situation poses more complex issues, as the SDI system has to be designed to prevent emitter clogging. Researchers concluded that once again proper management of the system is imperative to prevent emitter clogging and performance degradation, especially in the case of lower flow-rate emitters.

Modeling Yield

Functional Form

There are many functional forms used to model agricultural production. It is commonly accepted that agricultural production (as any other production activity) is subject to the law of diminishing marginal returns and production level tends to plateau at higher input levels. Linear functions imply that successive additional units of an input have the same effect on output as the first input unit, *ceteris paribus*, thus violating the law of diminishing marginal returns. Concave quadratic functions satisfy this law but are unrealistic since they assume nutrient units applied after the nutrient yield-maximizing level, decline yield (instead of a plateau, one has a peak). Other nonlinear functions that satisfy the above requirements and are more realistic have been studied.

Von Liebig developed a production function[4] that relies on the idea that production is determined by the constraining factor—this idea is sometimes referred to as Liebig's Law. The problems of such a function are its discontinuity and its rigidity, since it does not allow abundant factors to have an effect on yield if there is one constraining factor; hence it overlooks interaction effects between inputs (Beattie and Taylor, 1993). The Mitscherlich-Baule production function[5] overcomes both these problems and offers nice properties such as a positive interaction between production factors, partial substitution among production factors, and a sigmoid production curve (Nijland and Schouls, 1997). The M-B function is theoretically sound but since it is a nonlinear function in the parameters and the variables, its estimation has some computational burden. A useful discussion of crop yield response functions can be found in Nijland and Schouls (1997). Beattie and Taylor (1993) is a useful reference for production theory and production functional forms.

Nitrogen Considerations

The role of nitrogen as an essential nutrient to plant development has been widely studied by agronomists and soil scientists. Plants consume inorganic (or mineral) forms of nitrogen such as nitrate (NO_3^-) and ammonium (NH_4^+). Ammonium can be transformed into ammonia (NH_3) which volatilizes into the atmosphere, thus becoming

---

[4] Generally specified as $\mathrm{E}(Y)=\min\left(Y^{\max},\beta_{10}+\beta_{11}N,\beta_{20}+\beta_{21}P\right)$, where $Y^{\max}$ is attainable production if there are no constraining factors, *N* and *P* are inputs nitrogen and phosphorus, *Y* is yield, and β_{ij} are parameters.

[5] Specified as $\mathrm{E}(Y)=Y^{\max}\left\{1-\exp\left[\beta_{11}\left(\beta_{10}+N\right)\right]\right\}\left\{1-\exp\left[\beta_{21}\left(\beta_{20}+P\right)\right]\right\}$, with $\beta_{11}<0$ and $\beta_{21}<0$. Some authors refer to it as a Mitscherlich function when $\beta_{10}=\beta_{20}=0$.

unavailable for plant consumption. Other nitrogen losses which can occur are leaching, runoff, plant removal, and denitrification.

Plants obtain nitrogen from the indigenous nitrogen supply in the soil and/or from nitrogen applied to the soil. Ideally one would like to supply nitrogen to the soil so as to meet the plant requirements, given the level of nitrogen already available in the soil. A pertinent issue is whether the effect of soil nitrogen on yield is the same as the effect of applied nitrogen. This is basically questioning whether the coefficient of soil nitrogen and the coefficient of applied nitrogen in the estimated yield function are significantly equal or not. There is evidence from previous studies that the two coefficients are statistically different (Stoecker and Onken, 1989).

Much research has been conducted to develop technologies or management practices that improve nitrogen use efficiency (NUE), that is, reduce nitrogen losses and improve nitrogen uptake by plants. Some examples of such practices are incorporation of fertilizer in soil, plant rotations, use of soil tests, etc. However, this research is of little or no use to farmers unless these developments are shown to be cost-efficient or practical (Cassman, Dobermann, and Walters, 2002). Since nitrogen is quite affordable to farmers, it is common for farmers to over-apply nitrogen and disregard researchers' suggestions, which may allow short-term economic survival of farmers but poses long-term environmental concerns (Yadav, 1997; Raun and Johnson, 1999).

Another direction of agronomic research concerns the movement of different forms of nitrogen in production systems. Researchers have shown that the fates of nitrogen as nitrate and nitrogen as ammonium differ in field systems (Crozier, King, and Volk, 1998). Although no short-term significant differences in above ground plant or corn grain yield were found between nitrogen application as ^{15}N-enriched crimson clover and as fertilizer (NH_4NO_3), long-term corn yield was significantly greater for fertilizer nitrogen (ibid.). This difference is due to the fact that in warm, humid climates, applying nitrogen as enriched clover will yield a rapid mineralization, and consequently a disappearance from soil of inorganic nitrogen. Results from experiments in the Oklahoma Panhandle show that 37 to 57 percent of applied nitrogen in the form of ammonia (NO_3) can volatilize to the atmosphere as ammonium (NH_4) within a few days of swine effluent application to a Richfield clay loam soil, a calcareous type of soil (Zupancic, 1999, p. 64). The most important determinants of how much volatilization occurred were the climatic conditions following application. The most ammonia volatilization observed occurred during weather conditions that were “hot, dry, with very low relative humidity, and brisk wind speeds” (ibid., p. 56); the least levels of ammonia volatilization occurred during more humid, rainy weather (ibid., p. 39). Ammonia volatilization can be reduced by applying the effluent to a growing crop or to residue covered soil instead of fallow soil (Warren, Hattey, Turner, and Parton, 2000).

As mentioned above, given the instability of ammonium, part of the nitrogen applied is lost to the atmosphere through volatilization, thus the actual level of nitrogen available for the plant is random and unknown. Volatilization is closely related not only to weather patterns but also to management decisions. Johnson et al. (1995) estimated the probabilities of nutrient loss (phosphorus and nitrogen) from dairy waste application using qualitative risk assessment. The study developed an event tree to illustrate the sequence of hazardous situations in water management. The study did not incorporate risk due to weather patterns. Precursory work by Wu, Nofziger, Warren, and Hattey

(2003a, 2003, b) developed a method of estimating short term ammonia volatilization from application of swine manure to a field which accounts for the distribution of rainfall, temperature, and wind speed. Their model can be used to account for ammonia losses from sprinkler or from flood application of effluent.

Underlying Probability Distribution of Yield

Another issue surrounding production function estimation concerns the distributional assumption of yield. The evolution of statistic analysis and the way Statistics is used today is directly related to the absence of powerful computational tools when Statistics was developed (personal communication, Dr. Jeanne Hill, Baylor University). During many years, the normal probability distribution held a hegemonic position in statistical estimation, as the theory surrounding this distribution is well established and most statistical tests rely on the normality assumption.

Although widely used, many authors defend that the normal distribution is inadequate to model variables such as returns or yields (see Taylor, 1990). The normal distribution is defined by its first and second moments: the mean and the variance, which Taylor (1984) deems insufficient to handle problems with inherent risk, such as agricultural farming, which is generally viewed as a risky venture.

As computers have become more powerful and fast, we have seen the development of several different statistical packages (SHAZAM, SAS, SSPS, SPlus, etc.), estimation algorithms (Newton-Raphson, Nelder-Mead simplex optimization, trust region optimization, etc.), and estimation/simulation procedures (e.g. Monte Carlo studies, Kernel estimates, projection pursuit), which can handle more sophisticated distributional assumptions and functional forms, as well as larger amounts of data. Some of these estimation procedures rely on transforming nonnormal multivariate distributions into normal univariate distributions (Taylor, 1990). For the treatment of nonlinear functions, some procedures use Taylor series expansions as linear approximations to the nonlinear functions.

The counter-argument in favor of normality is that most of these variables are but averages (e.g. returns per acre, yield per acre), in which case the Central Limit Theorem is applicable and the variables are asymptotically normal (Just and Weninger, 1999). If that is the case, then why would these variables fail normality tests? Just and Weninger (ibid.) advance three possible reasons: 1) the nonrandom components are misspecified due to the use of detrending, 2) statistical significance is misreported because it is not correctly measured, and 3) use of aggregate time series data to represent farm-level yield distributions, which under-represents farm specific variation while emphasizing region wide effects.

The introduction of risk in yield estimation is another pertinent issue. In 1983, Harris, Mapp, and Stone concluded that soil moisture stress at certain plant growth stages, which is a consequence of irrigation choices, was more important in determining total grain sorghum yields than total amount of water applied, when farming in the Oklahoma Panhandle. Soil moisture stress is directly related to weather variation, a source of risk to production. Irrigation schedules that focused on the last stage of plant development before maturity were stochastically dominant over irrigation schedules that focused on earlier plant growth stages. In the above-mentioned study, optimal control theory was used to determine the optimal schedule of long-term groundwater use, assuming farm returns were maximized given constraints. The authors showed that irrigation scheduling could prolong the economic life of the aquifer in the region.

Economic Evaluation of Irrigation Systems

Research conducted at KSU shows that based on a 160 acre study area, center pivot system costs per irrigated acre are \$361 versus SDI system costs per irrigated acre of \$787.20 (O'Brien, Dumler, and Rogers, 2001). The study allows for differences in the total irrigated area between the two systems and assumes that part 26 acres cannot be irrigated with the center pivot and must be cultivated with dry land wheat. For the SDI, the total area irrigated in 155 acres, as five acres are lost due to turn rows.

In terms of net returns, previous research shows that for corn production, on a per acre basis, center pivot returns exceed SDI returns for field sizes of 160, 127, 95, 80, and 64 acres (excess net returns per acre are \$22.07, \$22.90, \$17.08, \$11.67, and \$1.09, respectively); for a 32-acre field size SDI net returns exceed center pivot net returns by \$11.08 per acre. Increases in corn yield or crop prices benefit SDI net returns. (O'Brien, Rogers, Lamm, and Clark, 1997). Thus it is possible that if one considers cumulative corn production over time, the SDI system becomes more profitable as it allows greater cumulative yield. Rutegård, Lönnstedt, and Kallio point out that one of the advantages of dynamic programming over a single period model consists of the ability of the multi-period model to "look ahead and adapt the current decisions to what might happen afterwards."

Stoecker, Seidmann, and Lloyd used linear dynamic programming to measure the benefits of planning the water use of the High Plains Aquifer over time. As the aquifer water table declines, crop choice moves from a water intensive crop such as corn, to cotton, and finally to dry land wheat, as the aquifer becomes economically depleted. The choice of when to move from one crop to the next is endogenous to the model. The study found that the water savings obtained from more water-energy efficient systems may provide greater economic benefits if used to expand current irrigation rather than stretching irrigation over time. This conclusion is very intuitive as we are moving from more profitable to less profitable crops over time. They found that the selection of the optimal irrigation system (low pressure central pivot or furrow distribution system) to use depends on the water table saturation thickness aquifer. The economic benefits of long run aquifer exploitation are likely to depend on the length of the planning horizon.

CHAPTER III

METHODOLOGY

Conceptual Framework

It is common to use a budget approach to evaluate the economic merit of alternative technologies. Budgeting is a necessary component to any study, but the present problem requires a more sophisticated approach to fully integrate the inherent risk component of farming over time with inadequate rainfall, limited freshwater resources, ammonia volatilization, and the possibility of phosphorus accumulation in the soil. In 1962, Bostwick defended that crop yield should be modeled as a Markov process because the distribution of the observational data is not random, i.e., “an autocorrelation ghost persists in stalking such models [the author refers to models that assume randomness], even though hidden in residual error terms” (Bostwick, p. 49). A Markov process assumes that the evolution of a variable from one state to the next follows probabilistic “laws of motion” (Hillier and Lieberman, 1980, p. 548). For example, this year’s yield and this year’s decision choices will determine a probabilistic distribution for next year’s yield. This reasoning can be taken one step further, if one considers that plant growth is divided into stages and management decisions in one stage affect plant development in the following stage. Harris, Mapp, and Stone (1983) used the latter idea and showed that in the case of irrigation of grain sorghum, amount of water applied and timing of application has an effect on final yield.

The development of yield and its distribution depend greatly on climatological factors and, in particular, on the temporal distribution of rainfall, evaporation and atmospheric temperature. The level of risk can be controlled by choosing an irrigation system that is water efficient, adequate levels of irrigation, and sound nutrient management practices. However, these inputs and/or practices also increase expected yield. Thus there are two different effects: on one hand, an increase in the average yield and, on the other hand, a decrease in the variance of the distribution of yield (Just and Pope, 2003). Advances in computer technology in recent years have made possible the use of more rigorous data in terms of accuracy and detail in agronomic research. This has made possible the construction of simulation programs such as EPIC, which can be used to generate agronomic data representative of certain management practices. Dynamic programming has greatly benefited from this advancement and the construction of Markov processes that consider climatological patterns has become easier.

Once a crop has been planted, yield can be influenced via the application efficiency of the irrigation system, irrigation level, and nutrient application. These decision areas help the farmer reduce yield variability due mainly to physical soil differences and atmospheric conditions. The question lies in choosing how much to apply, how to apply, and when to apply, so that the farmer maximizes his welfare over time, given the farmer's resource constraints. In the Oklahoma Panhandle, where animal manure is an abundant resource and water is a scarce resource, it is logical to assume that effluent collected from animal houses should be used as a source of water and nutrients for crops. But using animal effluent must conform to strict environmental regulation; and using aquifer water to supplement animal effluent must take into account the long-term use of the finite aquifer resources. Given the semiarid climate in the region, the method used to apply the effluent to the crop will also affect the amount of water and nitrogen that actually reach the plant.

Procedure

The empirical implementation of the present study relies on the completion of different steps: input data collection, simulation and generation of output data in EPIC, econometric estimation of response and carryover functions in SAS using output data, optimization of producer's welfare under different assumptions, and finally evaluation of alternative solutions under different risk scenarios. A graphical representation of how the different solutions used in the analysis were obtained can be seen in Figure 2. Data input into EPIC consisted of weather data as defined previously, geographical and geological characteristics of region (soil test results, type of soil, slope, etc.), management choices (effluent applied, urea applied, irrigation applied), and type of crop which in our case was irrigated corn or dry-land wheat.

After data were simulated in EPIC (see Appendix E for experimental design underlying the simulation), several econometric relationships were estimated (for soil nitrogen carryover, soil phosphorus carryover, nitrogen percolation, and irrigated corn yield), as well as a probability density distribution for ammonia volatilization. Ammonia volatilization is a concern mainly for the center pivot irrigation system.

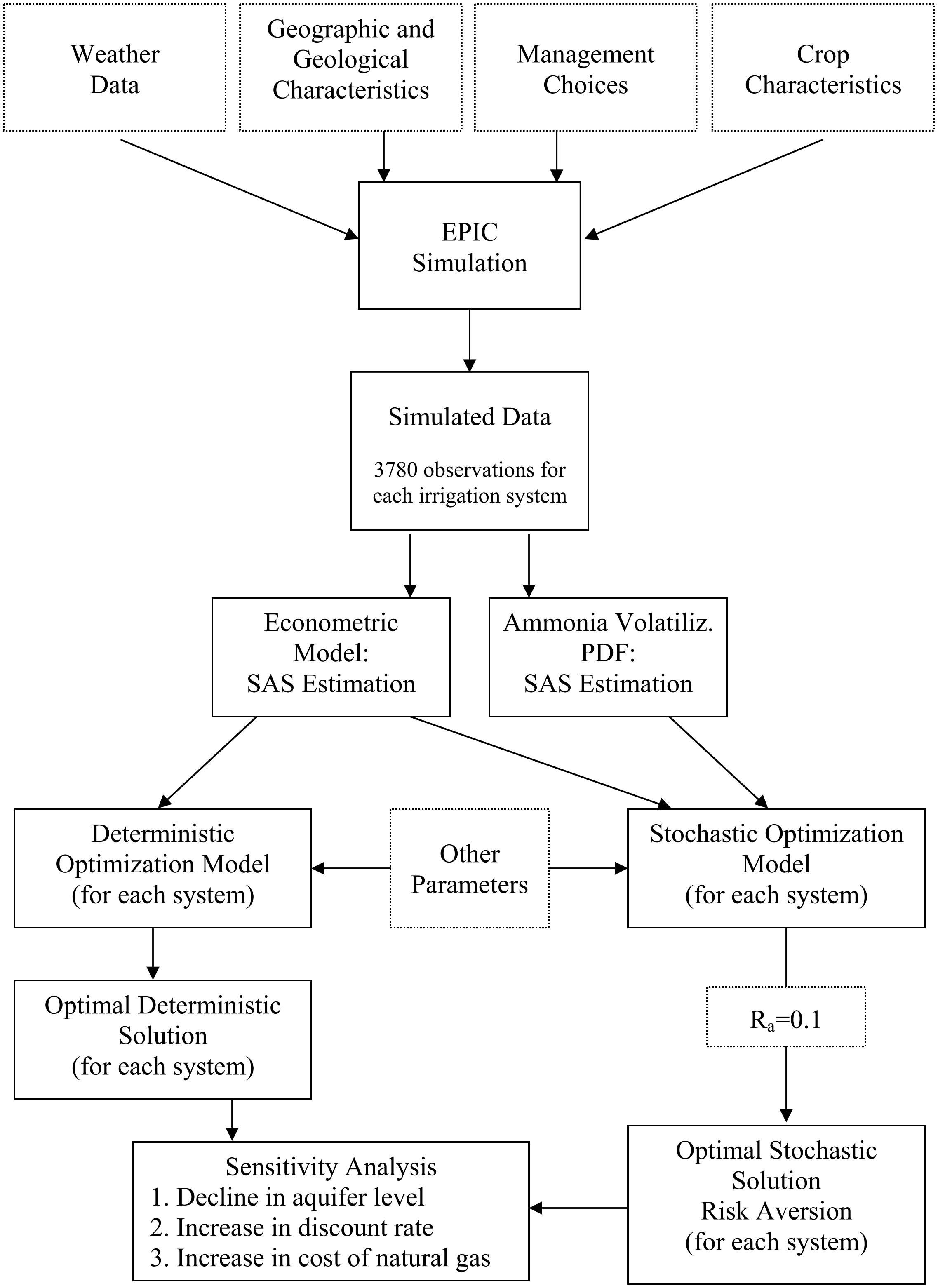


Figure 2. Graphical Representation of Study Implementation Procedure

Note: Dotted shapes indicate exogenous elements used in data generation and/or analysis.

From the EPIC yield simulations, it was estimated that on average for the center pivot, 24 percent of the nitrogen applied volatilizes as ammonia, while the SDI has an 8 percent volatilization rate (these values were obtained by computing the mean of ammonia volatilization for each irrigation system, see Appendix G).The percentage of ammonia volatilization is related to the type of irrigation system used, the amount of nitrogen applied, and its form (for example effluent nitrogen or commercial urea, see Appendix G), weather conditions, etc. Thus it is of interest to introduce ammonia volatilization as a source of risk in the model, which will be used to implement the stochastic models.

Risk can refer to many things, but one usually thinks of risk either as the possibility of a loss or the uncertainty of an outcome. A pertaining issue in risk analysis is what kind of risk behavior producers have in their activity. A common agreement is that producers are risk averse (at least with respect to losses), that is, they will usually engage in some sort of risk avoiding behavior such as irrigation, application of fertilizer, etc, which they believe will decrease the probability of a loss. Of course producers who are risk neutral also irrigate and apply fertilizer; the difference between risk-averse agents and risk neutral agents is in the amount of inputs applied. This amount, if agents behave rationally, is the optimal solution to the agent's optimization problem. The objective function of this problem is the agent's expected utility function, which is assumed to be a transformation of the producer's net revenue function (note that for a risk neutral producer, the utility function is a monotonic transformation of the expected net revenue function, thus maximizing expected utility is equivalent to maximizing expected net revenue). By considering the two stochastic solutions, we can ascertain the difference between the level of inputs applied because of pure risk aversion and the level of inputs applied to increase expected yield.

Dynamic Programming Optimization

The objective of the deterministic dynamic programming optimization is to maximize the present value of a stream of net returns over the production horizon, that is

$$\begin{aligned}\max_{G_t, F_t} NPV = \sum_{t=1}^{T} \Big\{ & \theta \cdot \left[P^c \cdot E\left(Y_t\right) - C^e \cdot F_t - \left(C^m - C^W \cdot W_t\right) \cdot G_t - OVC \right] \\ & - C^{IS} \left[r \big/ 1 + \left(1 + r\right)^{-\bar{Q}} \right] + \left(1 - \theta\right) \cdot R^w \Big\} \left(1 + r\right)^{-t} \end{aligned}, \qquad (2)$$

for each irrigation system, where P^c is the price of corn, $E\left(Y_t\right)$ is the expected yield of irrigated corn in year *t*, C^e is the unit cost of effluent, F_t is effluent applied, G_t is quantity of groundwater used in irrigation (in cm), W_t is the quantity of water in aquifer, C^W is the unit value of the water extracted, C^m represents maximum unit cost of pumping aquifer. Note that pumping costs, $\left(C^m - C^W \cdot W_t\right) G_t$, are set up so that they increase with the depth at which the remaining fresh water must be extracted from the aquifer. OVC represents other operating variable costs related to pesticide, corn seed, crop insurance, machinery fuel, lube, repairs, etc. The value for OVC was obtained from the OSU Enterprise Budget. C^{IS} represents the installation cost for the irrigation system. $\bar{Q}$ represents irrigation system life and *r* represents the interest rate. R^w represents the net revenue of growing dry land wheat, and θ_t is the proportion of the quarter section of land producing corn in year *t* (for the first year, if we use a center pivot, $\theta = .7875$; for the SDI, $\theta = 1$).

The choice variables are quantity of water used in irrigation and quantity of effluent applied.

$N_t = \sigma_N F_t$ and $P_t = \sigma_P F_t$, where σ_N is the proportion of nitrogen in effluent and σ_P is the proportion of phosphorus in effluent. In this case we are only interested in the nutrient value of effluent as either nitrogen or phosphorus as we are not concerned with other nutrients such as potassium. Assuming diminishing returns, the functional form for yield can be modeled as a modified Mitscherlich-Baule function, thus

$$\begin{gathered} Y_t = \left(\eta_{01} + \eta_{02} D\right)\left\{1 - \exp\left(\eta_{11} SN_t + \eta_{12} N_t + \eta_{13} U_t + \eta_{14} V_t\right)\right\}\left\{1 - \exp\left(\eta_{21} SP_t + \eta_{22} P_t\right)\right\} \\ \left\{1 - \exp\left(\eta_3 G_t\right)\right\} + \varepsilon_t \end{gathered}, \quad (3)$$

where $\eta_{01},\ldots,\ \eta_3$ are the parameters to be estimated. The parameters corresponding to input application ($\eta_{11}, \eta_{12}, \eta_{13}, \eta_{21}, \eta_{22}, \eta_3$) are assumed to be negative and the parameter corresponding to ammonia loss (η_{14}) is assumed to be positive, thus ensuring a concave yield function. The parameter η_{01} represents maximum attainable yield for the SDI system; η_{02} corresponds to the dummy variable *D*, which takes the value 1 for SDI and 0 for the center pivot irrigation—we expect this parameter to be negative, implying that the potential yield for SDI is greater than the potential yield for center pivot irrigation. V_t is the level of ammonia volatilization in year *t*, U_t is the level of urea applied in year *t*, SN_t is the level of nitrogen in the soil at year *t*, N_t is the level of nitrogen from effluent applied in year *t*; P_t and SP_t are similarly defined for phosphorus. ε_t is a heteroskedastic random error term distributed as $\varepsilon_t \sim N\left(0, \exp\left(\alpha_0 + \alpha_1 G_t\right)\right)$, which when

$\alpha_1 < 0$ implies that variance of yield declines as the irrigation level increases. The above functional form assumes that if there is no irrigation, corn yield is zero. Such an assumption is realistic for the area, as under a semiarid climate with inadequate rainfall, the production of irrigated corn is greatly constrained by irrigation.

The nitrogen carryover equation is defined as

$$SN_{t+1} = \lambda_0 + \lambda_1 SN_t + \lambda_2 N_t + \lambda_3 U_t + \lambda_4 Y_t + \lambda_5 K_t + \lambda_6 V_t + \vartheta_t, \tag{4}$$

where K_t represents deep nitrogen percolation, which is very relevant in SDI but is negligible for sprinkler irrigation, thus we hypothesize that $\lambda_4 = 0$ for this system. The parameters are not the same for both systems but the underlying hypotheses are $\lambda_3 < 0$, $\lambda_4 < 0$, and $\lambda_6 < 0$ while $\lambda_1 > 0$ and $\lambda_2 > 0$. The underlying distribution of the error term is $\vartheta_t \sim N\left(0, \exp\left(\phi_0 + \phi_1 G_t + \phi_2 N_t\right)\right)$. The variance of the error term is assumed to increase with the irrigation level, thus $\phi_1 > 0$.

The level of phosphorus available to the plant is a combination of soil phosphorus and phosphorus applied. The phosphorus carryover equation refers to labile phosphorus, i.e., phosphorus that is available for plant use. As a rule, phosphorus is not a mobile nutrient in the soil unless it is present in such excessive amounts that it is transported through water (phosphorus runoff) and wind erosion. The phosphorus carryover constraint is defined as

$$SP_{t+1} = \delta_0 + \delta_1 SP_t + \delta_2 P_t + \delta_3 Y_t + \varpi_t, \tag{5}$$

and we assume that $\delta_1 > 0$, $\delta_2 > 0$, $\delta_3 < 0$, and $\varpi_t \sim N\left(0, \exp\left(\kappa_0 + \kappa_1 G_t + \kappa_2 P_t\right)\right)$, where increasing the level of irrigation decreases variance of soil phosphorus , i.e., $\kappa_1 < 0$.

Since the application of nitrogen with a center pivot causes a significant amount of nitrogen to be lost through volatilization, but the amount of nitrogen that seeps through the soil is negligible, a nitrogen percolation function will not be estimated for this system. In the case of SDI, deep nitrogen percolation is of concern and this function is defined as

$$K_{t+1} = \exp\left(\gamma_0 + \gamma_1 SN_t + \gamma_2 N_t + \gamma_3 U_t + \gamma_4 Y_t + \gamma_5 G_t N_t + \gamma_6 G_t SN_t + \xi_t\right). \tag{6}$$

The error term is distributed normal as $\xi_t \sim N\left(0, \exp\left(\varphi_0 + \varphi_1 G_t\right)\right)$ and it is expected that $\gamma_1, \ldots, \gamma_3 > 0$, while $\gamma_4 < 0$; the interaction terms are assumed to have a positive effect on nitrogen percolation. The source of variance is once again irrigation. The above equation can be made linear in the parameters and error term by taking a log transformation of both sides.

The water supply constraint is a balance equation, in which we assume the decline in the water table is due to irrigation only and there is no recharge of the aquifer. The remaining water supply is defined as

$$W_{t+1} = W_t - G_t. \tag{7}$$

The first stage to implement the dynamic optimization is to estimate the econometric functions in SAS. Yield is estimated with procedure NLMIXED. The carryover equations will be estimated using procedure AUTOREG in SAS, designed for estimation of functions linear in the parameters and error term but with flexible variance-covariance structures. Following the econometric estimation, the model will be assembled in Excel. The optimal solution will be identified using a GAMS model type NLIN, solver CONOPT. If this algorithm does not perform well, a Solver add-in in Excel which implements standard generalized reduced gradient (GRG) nonlinear method optimization will be used.

Stochastic Dynamic Programming Optimization

The main assumption for this part of the study is that, although nitrogen application to the plant depends on the level of soil nitrogen already in the soil, the level of nitrogen that actually is available to the plant is unknown because nitrogen volatilization is random. Nitrogen volatilization is higher with center pivot sprinkler irrigation compared to SDI. The level of soil moisture in the soil is also unknown due to random evaporation levels, but at this point the soil moisture effect will not be considered in the Markov process due to lack of data.

The level of yield attained follows a probability distribution, which depends on the decisions made by the producer in terms of irrigation, effluent applied, and urea applied. The level of yield obtained in one year should have an effect on next year's yield level, since yield outcome affects the amount of residual nutrients in the soil. Thus one can think of yield as a Markov process in which "the distant past is irrelevant given knowledge of the recent past."[6] A process is called Markovian if it has the Markov property defined as "'the future depends only on the present, not on the past'; that is, if the probability distribution of future states of the process depends only upon the current state and is conditionally independent of the past states (the path of the process) given the present state."[7] For the yield process to satisfy the Markov property, the following statement must be true:

$$\Pr\left(Y_{t+1} \mid Y_1, Y_2, \ldots, Y_t\right) = \Pr\left(Y_{t+1} \mid Y_t\right). \tag{8}$$

---

[6] http://en.wikipedia.org/wiki/Markov_chain

[7] http://en.wikipedia.org/wiki/Markov_property

This implies that yield level in year $t+1$ depends only on yield level of year *t*. Recall that each year's yield level is a random variable. The use of Markov chains to model yield has been pursued in past literature by authors such as Bostwick (1962) and Valentine and Furnival (1989).

Assume that corn yield can be classified into one of three states: low, average, or high (mathematically define state with the letter *Z*). Assume in year *t* the farmer implements decision choice *d,* where ($d = d_1, ..., d_D$), consisting of a certain level of irrigation, urea, and effluent applied. Then in the following year, yield has a certain probability distribution of being in each state level ($Z = 1, ..., \bar{Z}$). The probability of moving from one state to another is known and is defined as

$$\Pr\left(Z_{t+1} = z_{t+1} \mid Z_t = z_t, d\right) = p_{z_t, z_{t+1}}(d), \tag{9}$$

and $0 \le p_{z_t, z_{t+1}}(d) \le 1$ and $\sum_{z_{t+1}=1}^{\bar{Z}} p_{z_t, z_{t+1}}(d) = 1$. These probabilities can be assembled in a transition matrix (shaded portion of Table 5), which determines the stochastic process resulting from the stochastic nature of nitrogen availability. Each decision is associated with a different transition matrix. Each irrigation system is associated with different probabilities. A Markovian decision process refers to the sequence over time of observed yield states and to the sequence of decisions taken (Hillier and Lieberman, 1980, p.553).

Table 5. Example of a Transition Matrix for a Markov Chain Given Decision d_1

State z_t \State z_{t+1}	Low	Average	High	Sum
Low	$p_{11}(d_1)$	$p_{12}(d_1)$	$p_{13}(d_1)$	1
Average	$p_{21}(d_1)$	$p_{22}(d_1)$	$p_{23}(d_1)$	1
High	$p_{31}(d_1)$	$p_{32}(d_1)$	$p_{33}(d_1)$	1

To estimate the probabilities used in the Markov Chain, one must first consider the source of randomness, which we assume is ammonia volatilization. Following the work of Taylor (1984), one can use a hyperbolic tangent function to estimate a probability distribution function with a closed form CDF. This PDF has a bell shape, yet it is flexible enough to incorporate skewness, thus it need not be symmetric.

Since ammonia volatilization (*V*) is a physical measure, $0 \le V < +\infty$. We know that given a variable *x*, such that $-\infty < x < +\infty$, then the hyperbolic tangent of *x* is defined as

$$\tanh\left(x\right) = \frac{e^{2x} - 1}{e^{2x} + 1} \tag{10}$$

and $-1 < \tanh\left(x\right) < 1$. This function can be transformed as follows to yield a function with [0, 1] boundary:

$$0 \le 0.5 + 0.5\tanh\left(x\right) \le 1 . \tag{11}$$

The first derivative of the above function with respect to *x* and corresponding boundary are given by

$$0 \le 0.5\cosh^{-2}\left(x\right) \le 1 . \tag{12}$$

If one considers a transformation of ammonia volatilization, $\Psi\left(V\right)$, such that $\lim_{V \to 0}\left[\Psi\left(V\right)\right] = -\infty$ and $\lim_{V \to +\infty}\left[\Psi\left(V\right)\right] = +\infty$, then we can use the hyperbolic tangent transformation to compute a CDF of ammonia volatilization, since

$$0 \le 0.5 + 0.5\tanh\left[\Psi\left(V\right)\right] \le 1 . \tag{13}$$

A suitable transformation of ammonia volatilization is

$$\Psi\left(V \middle| N, U\right) = \rho_0 + \rho_1 V + \rho_2 V^{-1} + \rho_3 N + \rho_4 U , \tag{14}$$

which, as will be shown below, satisfies the conditions for a PDF if $\rho_1 > 0$ and $\rho_2 < 0$. The magnitude of the parameters and effluent nitrogen (*N*) and urea (*U*) terms allow the PDF to be bell shaped, as well as kurtotic. Note that when ρ_1 and ρ_2 have different magnitudes, the distribution becomes skewed. The transformation proposed in equation (13) differs from the one proposed in Taylor (1984), which is of the type

$$\Gamma\left(V\middle|N,U\right) = \rho_0 + \rho_1 V + \rho_2 V^2 + \rho_3 N + \rho_4 U \,. \tag{15}$$

Clearly this transformation poses a problem as $\lim_{V\to 0}\left[\Gamma\left(V\middle|N,U\right)\right] = \rho_0 + \rho_3 N + \rho_4 U$, which implies that

$$\lim_{V\to 0}\tanh\left[\Gamma\left(V\middle|N,U\right)\right] \neq -1 \,, \tag{16}$$

thus Taylor's (1984) transformation does not yield a true PDF.

Given the ammonia volatilization CDF described in equations (12) and (13), the PDF of ammonia volatilization is defined as

$$f\left(V\middle|N,U\right) = \frac{\mathrm{d}}{\mathrm{d}V}\left[0.5 + 0.5\tanh\left(\rho_0 + \rho_1 V + \rho_2 V^{-1} + \rho_3 N + \rho_4 U\right)\right], \tag{17}$$

which yields

$$f\left(V\middle|N,U\right) = 0.5\left(\rho_1 - \rho_2 V^{-2}\right)\cosh^{-2}\left(\rho_0 + \rho_1 V + \rho_2 V^{-1} + \rho_3 N + \rho_4 U\right). \tag{18}$$

Since $f\left(V\middle|N,U\right) \geq 0, \forall V \in \mathbb{R}_0^+$ and $\int_0^\infty f\left(V\middle|N,U\right)\mathrm{d}V = 1$, the above is a PDF (see proof in Appendix D).

The objective of the stochastic dynamic model is to maximize expected utility of net returns over time and initial wealth (Ω), given the constraints faced by the producer and the probability distribution of ammonia volatilization, by choosing the optimal irrigation system (subsurface drip irrigation or sprinkler irrigation, designated by *H*) and the optimal decision path (Δ_d), i.e.,

$$\max_{H,\Delta_d} E\left[\frac{U_t\left(\pi_t+\Omega\right)}{\left(1+r\right)^t}\right]. \tag{19}$$

The utility function assumed is a power function

$$U_t\left(\pi_t+\Omega\right)=\frac{\left(\pi_t+\Omega\right)^{1-\psi}}{1-\psi}, \tag{20}$$

where ψ refers to the coefficient of relative risk aversion. In the power function the Arrow-Pratt absolute risk aversion coefficient is $\psi/\left(\pi_t+\Omega\right)$, computed by taking the negative of the ratio of the second derivative of the utility function to the first derivative of the uitility function with respect to total wealth. The relative risk aversion coefficient is given by the parameter ψ, as mentioned above. This utility function exhibits the following desirable properties: decreasing absolute risk aversion and constant relative risk aversion (Pope and Just cited in Gray, Boehlje, Gloy, and Slinsky, 2004). The stochastic dynamic programming optimization model will be implemented using an optimization procedure written in Visual Basic Applications developed for this purpose (see appendix H).

CHAPTER IV

FINDINGS

Validation of EPIC Data

The first part of this study required the econometric estimation of several response functions and two probability density functions. Since the data used in the study were simulated in EPIC, some might question the legitimacy of using expressions such as “statistical significance” or “even probability distribution.” Opinions are divided regarding this issue. Many of the functions used by EPIC to generate the simulated data are the result of many years of field experiments. The validation of these functions was consistent with statistical theory and thus many of the variables follow statistical distributions. By generating data in EPIC, we essentially sampled from these statistical distributions. The clear advantage of simulation lies in the possibility of exact replication of the experiment since exogenous factors are truly exogenous. In real world experiments one cannot entirely replicate agricultural experiments as there are always some factors that we assume exogenous but in reality are endogenous even if their effect in the experiment can be considered minute (or statistically insignificant). Thus it can be argued that it is not farfetched to look at statistical significance of the function estimates obtained in SAS. Appendix F contains summary statistics of the yield data generated by

EPIC as well as an overview of previous work that reports irrigated corn yields for Texas County and for regions with similar conditions.

Econometric Estimation Results

The dry-land corn yield response function to irrigation, nitrogen, and phosphorus was implemented using procedure NLMIXED in SAS. The method used in the estimation was maximum likelihood; the maximum likelihood estimator is asymptotically normal, thus statistical tests based on the normal distribution can be used for large samples. The functional form assumed for the yield function was a modified Mitscherlich-Baule function, which is nonlinear in the parameters and variables but linear in the error term. It was assumed that yield was heteroskedastic with the irrigation level. To ensure a concave yield function with respect to input applications, the parameters associated with inputs must be negative while the parameter associated with ammonia volatilization must be positive. The parameter estimates for the yield function are reported in Table 6.

All parameters have expected signs, thus validating the simulated data obtained from EPIC. The magnitude of the effect of each variable on yield (marginal effect) is not equal to the parameter estimate of the variable, as the marginal effect with respect to one variable[8] is a function of the remaining variables as well as parameters. SAS procedure NLMIXED reports approximate standard errors of the parameter estimates computed with the Delta method, which can be used to compute approximate t-statistics.

---

[8] This is given by the first partial derivative of yield with respect to the variable of interest.

Table 6. Maximum Likelihood Parameter Estimates of Irrigated Corn Yield Function Computed With the Gauss-Newton Method in SAS Procedure NLMIXED

Variable	Symbol	Parameter Estimates	Approximate Std. Error
Maximum attainable yield for SDI	η_{01}	13.3885	0.0600
Adjustment of η_{01} for center pivot	η_{02}	-0.5075	0.0441
Soil nitrogen	η_{11}	-0.3047	0.0119
Effluent nitrogen	η_{12}	-0.0070	0.0004
Urea	η_{13}	-0.0104	0.0008
Ammonia volatilization	η_{14}	0.0376	0.0017
Soil phosphorus	η_{21}	-0.4918	0.1108
Effluent phosphorus	η_{22}	-0.1613	0.0184
Irrigation	η_3	-0.5176	0.0064
Variance intercept	α_0	1.5850	0.0411
Variance due to irrigation	α_1	-0.2897	0.0115

Notes: All parameters significant at the 5 percent significance level. N=7,560.

All parameter estimates are significantly different than zero at the 5 percent significance level. The pseudo-intercept shifter parameter corresponds to a dummy variable which takes the value of 1 if the irrigation system is the center pivot sprinkler and 0 for the SDI. The parameter estimate for the irrigation system dummy variable is statistically significant at the 5 percent significance level. Its negative sign indicates that potential yield under center pivot sprinkler irrigation is lower than under subsurface drip irrigation, which is consistent the initial hypothesis that for a certain input level, SDI achieves a greater yield than center pivot—this is in accordance with the information gathered from experimental data at different locations (Appendix F). The slope of the variance equation is negative indicating that increasing irrigation reduces yield heteroskedasticity; a result that was expected.

The equation for soil nitrogen carryover was estimated with maximum likelihood implemented with procedure AUTOREG in SAS, given our initial assumption of heteroskedasticity due to irrigation and amount of nitrogen in effluent applied. The parameter estimates for this regression are reported in Table 7.

Table 7. Soil Nitrogen Carryover Equation Maximum Likelihood Parameter Estimates Computed in SAS Procedure AUTOREG

Variable	Symbol	Parameter Estimates	Approximate Std. Errors
Intercept	λ_0	2.3465	0.0435
Lag of soil nitrogen	λ_1	0.9946	0.0001
Effluent nitrogen	λ_2	0.0390	0.0003
Urea	λ_3	0.0413	0.0003
Corn yield	λ_4	-0.7993	0.0051
Nitrogen percolation	λ_5	-0.0482	0.0010
Ammonia volatilization	λ_6	-0.0361	0.0016
Variance intercept	ϕ_0	0.6208	0.0138
Variance due to irrigation	ϕ_1	0.0635	0.0098
Variance due to effluent N	ϕ_2	0.0029	0.0002

Notes: All parameters significant at the 5 percent significance level. *N*=7,560.

Normality was rejected with a p-value inferior to 0.0001, which implies that the distribution of soil nitrogen is not normal. However, the estimators for the regression parameters are asymptotically normal thus statistical tests based on the normal distribution are asymptotically valid. The Lagrangean multiplier test of heteroskedasticity is based on a Chi-square distribution. The p-value for the test was smaller than 0.0001 indicating that we reject the null hypothesis of homoskedasticity in favor of the alternative hypothesis of heteroskedasticity. The parameter estimates of the variance equation were significantly different from zero. The signs of the slope parameters were positive indicating that the variance of soil nitrogen increases as the irrigation level increases—a possible explanation for this is that the speed of decomposition of organic nitrogen into ammonium is affected by the level of soil moisture, which is closely related to irrigation (Camperato et al.); and also as the level of effluent nitrogen applied increases, as was hypothesized earlier. The parameter estimates all have expected signs and are statistically significant at the 5 percent significance level.

The equation for soil phosphorus carryover was also estimated with maximum likelihood to account for heteroskedasticity. Parameter estimates are reported in Table 8. Once again the normality hypothesis was rejected at the 5 percent significance level. Homoskedasticity was rejected as well, and the parameter estimates for the heteroskedasticity equation were statistically significant. From these, we can assume that heteroskedasticity of soil phosphorus increases with the level of phosphorus applied and it declines with the level of irrigation applied. The parameter estimates for the carryover equation were all significant at the 5 percent significance level and exhibited the correct signs.

Table 8. Soil Phosphorus Equation Maximum Likelihood Parameter Estimates Computed in SAS Procedure AUTOREG

Variable	Symbol	Parameter Estimates	Approximate Std. Errors
Intercept	δ_0	-0.5004	0.2275
Lag of soil phosphorus	δ_1	0.9915	0.0035
Effluent phosphorus	δ_2	0.0617	0.0123
Corn yield	δ_3	-0.0942	0.0244
Variance intercept	κ_0	4.0148	0.0816
Variance due to irrigation	κ_1	-0.2248	0.0082
Variance due to effluent P	κ_2	0.0691	0.0010

Notes: All parameters significant at the 5 percent significance level. *N*=7,560.

Initially, the estimation of the nitrogen percolation equation was done with maximum likelihood, as it was expected that nitrogen percolation was heteroskedastic. Several sources of heteroskedasticity were tested (such as amount of nitrogen applied from effluent, irrigation, soil nitrogen) but the Lagrange multiplier test of heteroskedasticity failed to reject homoskedasticity. Thus the equation was estimated via OLS. The R-square for the estimation is extremely low (0.035) indicating a poor fit (Table 9). Several functional forms were tested but the fit did not improve. The lack of fit may be due to the fact that the simulated data contained many values for nitrogen percolation that were zero. To account for this, we also attempted to estimate nitrogen percolation using a censored regression estimation procedure, where the MLEs are approximated by dividing the OLS estimates by the proportion of non-zero values in the sample (Greene, p. 912).

Table 9. OLS Parameter Estimates for Log of Nitrogen Percolation Equation Computed in SAS Procedure AUTOREG

Variable	Symbol	Parameter Estimates	Approximate Std. Errors
Intercept	γ_0	-6.4983*	0.2503
Soil nitrogen	γ_1	0.0158*	0.0043
Effluent nitrogen	γ_2	-0.0102*	0.0017
Urea	γ_3	-0.0102*	0.0017
Corn yield	γ_4	0.3219*	0.0335
Irrigation-N applied interaction	γ_5	0.0005**	0.0003
Irrigation-soil nitrogen interaction	γ_6	0.0037*	0.0015

Notes:
* Parameter significant at 5 percent significance level.
**Parameter significant at 15 percent significance level.
N=7,560, R-square =0.035

But these estimates had a tendency to overestimate nitrogen percolation which in the SDI optimization model meant that soil nitrogen could become negative, which was impossible. Thus, for the sake of convergence and despite the poor fit, the OLS parameters were used.

Static Budget Analysis

As discussed earlier, it is common for people to use a static cost-benefit analysis to evaluate alternative decisions. In our case, we are interested in comparing the use of alternative irrigation systems: a subsurface drip irrigation system and a center pivot sprinkler irrigation system. It was previously argued that a static analysis may not capture certain aspects of the problem, such as declining water table, production horizon, constrained land, etc. The static budget analysis is presented in Table 10 and it shows that center pivot sprinkler irrigation is economically more profitable than SDI.

The main drawback of SDI is its high implementation cost, which is about 2.5 times higher than the implementation cost of the center pivot in the context of a quarter-section. The SDI does have a higher yield and even allows for corn production over a larger portion of the quarter-section, but these benefits are not enough to overcome its higher implementation cost. Thus, on a quarter-section, the center pivot's net revenues exceed the SDI's net revenue by over $700.

Table10. Static Budget Comparison for a Quarter-Section Irrigated Corn Production under SDI and Center Pivot

	Annual Returns and Costs by Irrigation System[1]					
	Subsurface Drip Irrigation			Center Pivot Sprinkler Irrigation[2]		
Budget Items	Avg. Quant.[3]	Per Hectare	Quarter Section	Avg. Quant.[3]	Per Hectare	Quarter Section
Revenue						
Irrigated corn	11.66	$1,194	$74,865	11.73	$946	$61,223
Dry-land wheat		--	--		$12	$748
Costs						
Effluent (valued as N[4])	152	$24	$1,506	232	$29	$1,871
Irrigation system[5]		$164	$10,294		$72	$4,651
Irrigation & Pumping	413	$553	$34,658	469	$435	$28,157
Other variable costs		$282	$17,715		$222	$14,401
Net revenue		$171	$10,692		$188	$11,396

Notes:

1. Averages used for this budget were obtained from the optimal solutions of the deterministic models. Values rounded to the nearest dollar.
2. Per hectare amounts are reported as a weighted average assuming quarter-section has 50.99 hectares producing irrigated corn and 13.76 hectares producing dry-land wheat.
3. Quantities are in the following units: mt/ha for yield, kg/ha for effluent nutrients, and mm/ha for irrigation
4. The monetary value of effluent was computed as the value of nitrogen in effluent.
5. Irrigation system cost is amortized over 15 years at a discount rate of 5 percent.

Deterministic Dynamic Optimization Results

Initially the deterministic optimization procedure was supposed to be implemented in GAMS IDE (version 2.0.23.10). Several algorithms were used in GAMS in an attempt to obtain reliable and realistic results: MINOS5, CONOPT2, and CONOPT3. CONOPT3 was the only algorithm to converge and successfully provide an apparently optimal solution, but a closer look at the solution revealed that the results were unrealistic as they were inconsistent with theory (for example, input use increased over time instead of decreasing). The next step was to use a standard generalized reduced gradient nonlinear algorithm contained in a Premium Solver add-in for Excel, obtained from Frontline Systems, Inc, a software company located in Incline Village, Nevada, which develops solvers/optimizers for Microsoft Excel, Lotus 1-2-3, and Quattro Pro. The results obtained from this optimization procedure were more satisfactory and consistent with theory and are reported below.

The amount of water irrigated per hectare starts out very similar for both systems (5.04 dm per hectare for SDI and 4.93 dm per hectare for center pivot), but over time less water is used with SDI per hectare (Figure 3). One of the assumptions of this study was that for each irrigated hectare, there were five hectares containing underground water in the aquifer. Although we start with the same amount of water for the quarter-section under both systems (Figure 4), in terms of amount of water per hectare, the SDI has less because it irrigates a bigger portion of land.

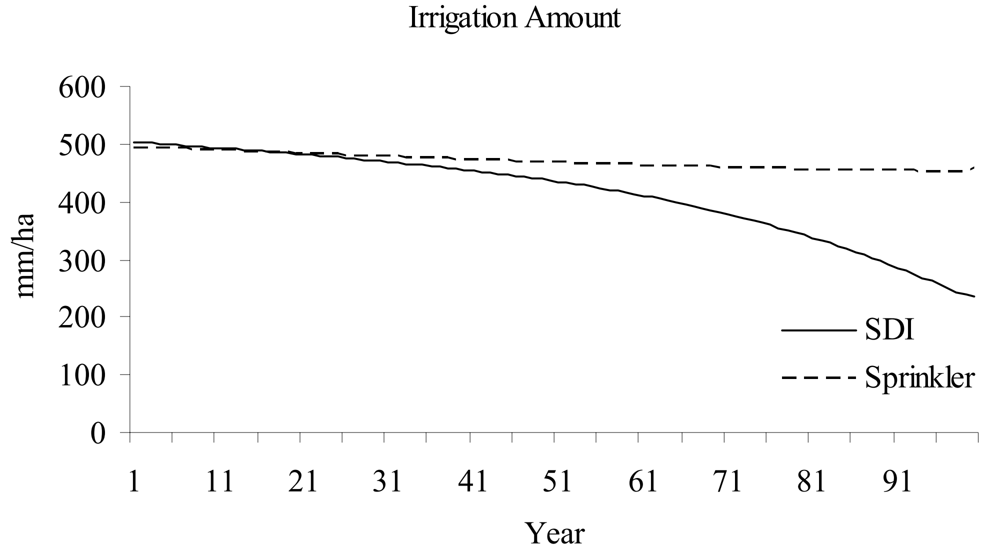


Figure 3. Projected Amount of Water Used in Irrigation of Corn by Each Irrigation System for the 100-Year Production Horizon Using the Deterministic Optimization Procedure Assuming the Quarter Section Has 323 ha of Aquifer Available for Water Extraction with Each Hectare Having 16.15 m of Water-Saturated Sand with 15% Aquifer Specific Yield

Thus, it is not surprising that when one looks at the remaining water supply, the difference between each system gets smaller over the production horizon (Figure 5). Cumulatively, over 100 years and over the quarter section, more water is used with the SDI (25,910 dm for SDI vs. 23,942 dm for center pivot) but on a per hectare basis the SDI ends up using less water over the production horizon (413 vs. 469 dm). In terms of amount of water irrigated per metric ton of yield obtained, the SDI system used on average 0.35 dm per hectare while the center pivot sprinkler used 0.4. All these results are consistent with the initial hypothesis of this study that SDI would be more water efficient than center pivot sprinkler irrigation.

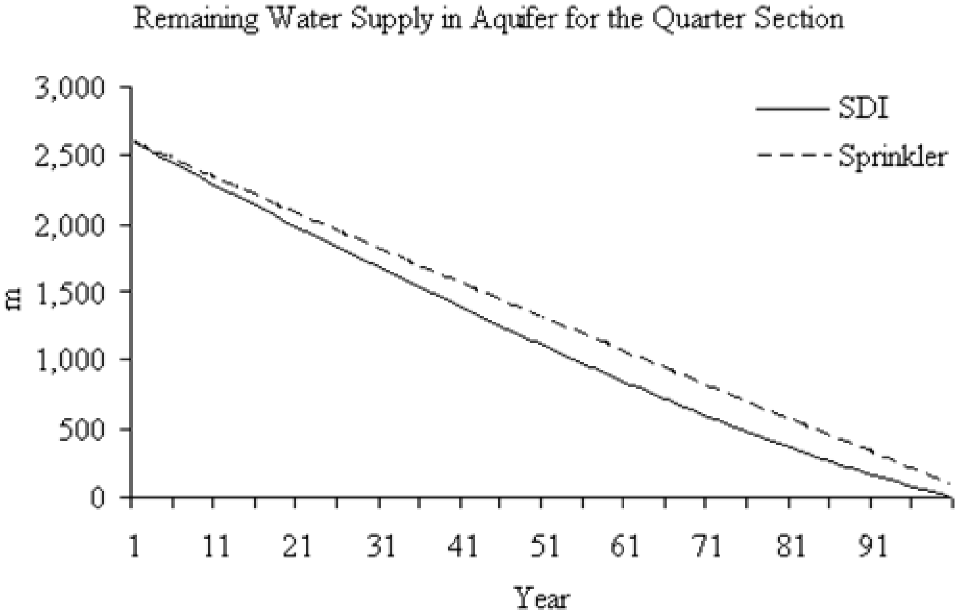


Figure 4. Projected Amount of Remaining Water in Aquifer for Quarter Section Under Each Irrigation System for the 100-Year Production Horizon Using the Deterministic Optimization Procedure Assuming the Quarter Section Has 323 ha of Aquifer Available for Water Extraction with Each Hectare Having 16.15 m of Water-Saturated Sand with 15% Aquifer Specific Yield

Less nutrient amounts are applied with the SDI, as expected, both on a per hectare basis (Figure 6), cumulatively over time (19,435 kg/ha for SDI vs. 29,772 kg/ha), and cumulatively over time and over the total quarter section (1,219,159 kg for SDI and 1,518,368 kg for center pivot sprinkler irrigation).

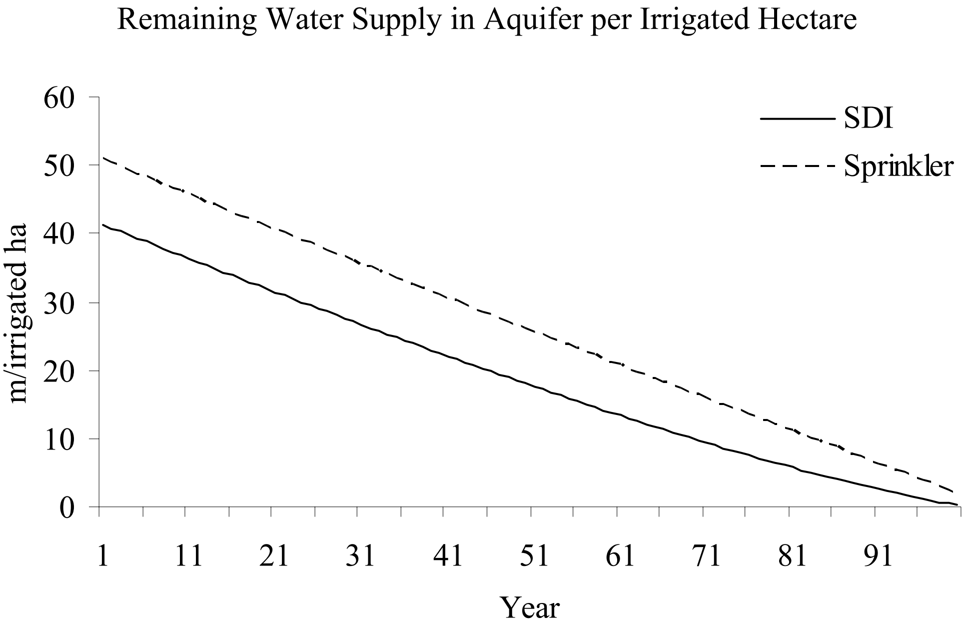


Figure 5. Projected Amount of Remaining Water in Aquifer per Irrigated Hectare for Each Irrigation System for the 100-Year Production Horizon Using the Deterministic Optimization Procedure Assuming the Quarter Section Has 323 ha of Aquifer Available for Water Extraction with Each Hectare Having 16.15 m of Water-Saturated Sand with 15% Aquifer Specific Yield

For the scope of this study, it was assumed that the nitrogen-phosphorus ratio was 3.55 which meant that for each kg of nitrogen and phosphorus in effluent, 78 percent was nitrogen (NO_3^-, NH_3, and NO) while the remaining 22 percent was phosphorus (although other nutrients are present in effluent, their effect was beyond the extent of this study).

Initially, urea was going to be used as an additional choice variable in the model, but the inclusion of urea created convergence problems for the optimization model, which could not be overcome, thus we chose to drop it from the optimization.

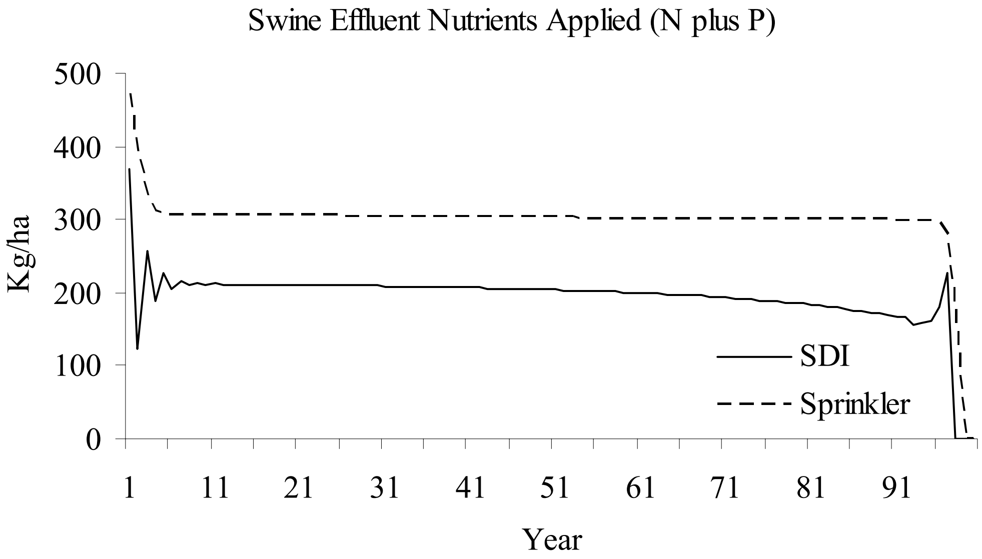


Figure 6. Projected Amount of Swine Effluent Nutrients Applied (Nitrogen plus Phosphorus) under Each Irrigation System for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

Less soil nitrogen accumulation per hectare occurred with SDI over time and the level of soil nitrogen remained very stable for both systems during much of the production horizon (Figure 7) indicating that with both systems the removal rate (through yield removal, nitrogen percolation, and ammonia volatilization) was very similar to the application rate of effluent nitrogen. Average soil nitrogen was 21.32 kg/ha for SDI and 24.54 kg/ha for sprinkler irrigation. The sudden drop (as well as the peak for the SDI) at the end of the planning horizon is due to the lack of end conditions imposed during the optimization.

Previous research by authors such as Sharpley et al.(1991) indicated that over time, soil phosphorus in effluent-treated-soil tends to increase (because phosphorus tends to be less mobile than nitrogen) which may pose serious issues for water quality in case of abnormally heavy rainfall events or even due to soil erosion created by the action of wind and/or water. This study had hypothesized that phosphorus accumulation would be greater in areas where effluent was applied with center-pivot sprinkler irrigation.

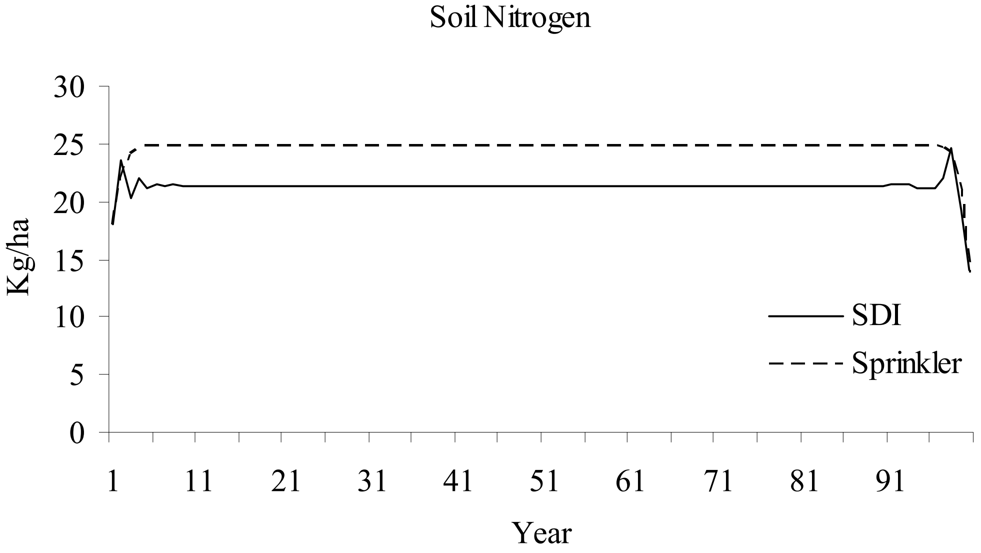


Figure 7. Projected Accumulation of Nitrogen in Soil under Each Irrigation System for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

The results of the deterministic optimization confirm this hypothesis as can be seen in Figure 8. Once again, recall that with the SDI, effluent is spread over a larger area, thus less phosphorus ends up in the soil on average (average soil phosphorus accumulation was 100 kg/ha for SDI vs. 125 kg/ha for center pivot sprinkler irrigation). Notice how, over time, the spread between the two systems becomes wider.

Irrigated corn yield per hectare was slightly higher for SDI during the first 60 years of the production horizon. It was previously hypothesized that SDI would permit a higher yield since it is more water and nitrogen efficient. While this hypothesis seems to hold for the first part of the production horizon, it does not hold all the time (Figure 9).

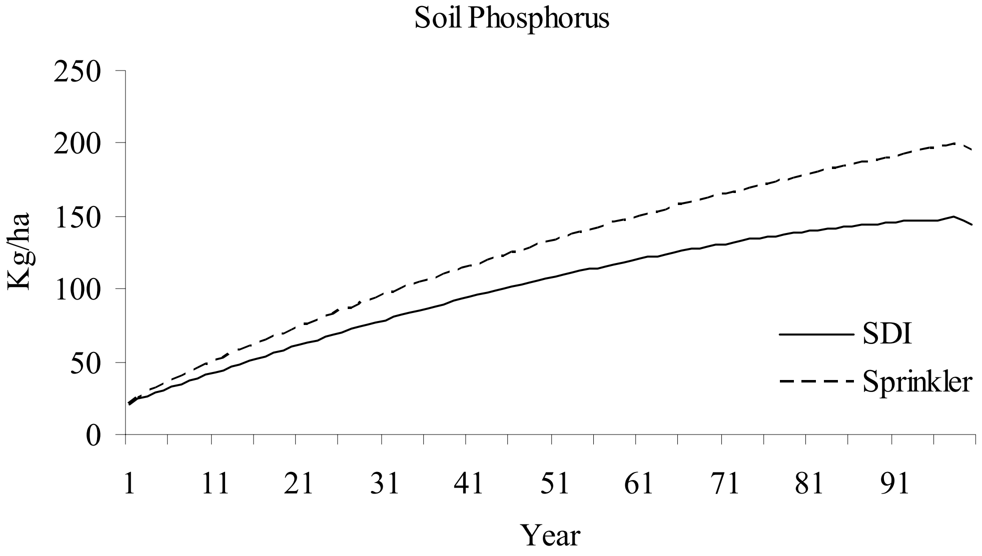


Figure 8. Projected Accumulation of Soil Phosphorus under Each Irrigation System for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

Average corn yield for the SDI was 11.66 tons/ha while for the center pivot irrigation it was 11.73 tons/ha. However, one must take into account that more area is irrigated with SDI than with sprinkler, given a constrained water supply, thus a larger area is cultivated with irrigated corn under the SDI than with center pivot irrigation. The direct implication is that cumulative corn production over the quarter-section is greater with the SDI (73,143 metric tons vs. 59,832 metric tons). Since irrigated corn is much more profitable than dry-land wheat, this effect is exacerbated over time (Figure 10) having serious implications for the profitability of each irrigation system.

As mentioned in the econometric results, the estimation of the nitrogen percolation equation yielded parameters which tended to under-estimate nitrogen percolation. The levels of percolation predicted in both models were very small, almost negligible for both systems.

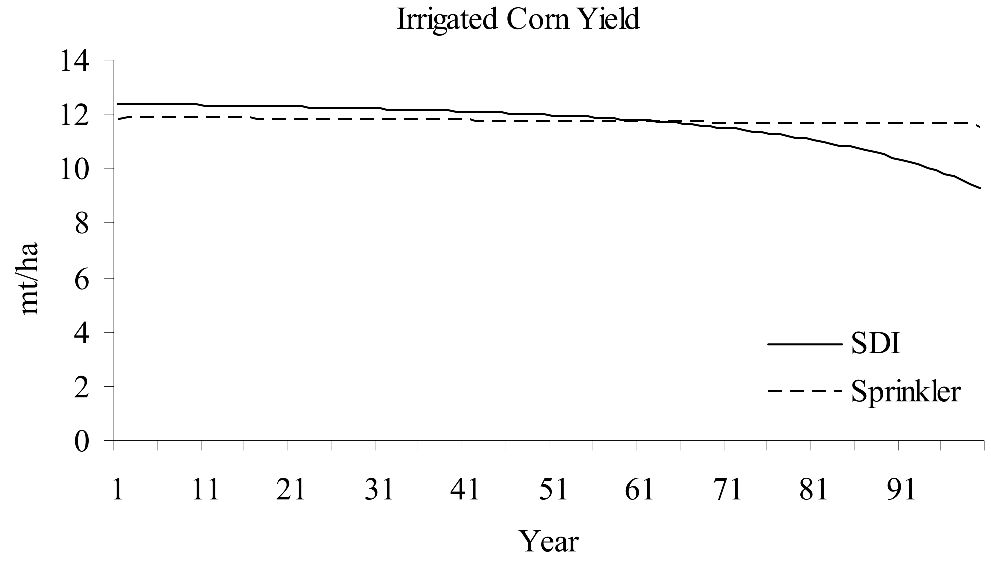


Figure 9. Projected Irrigation Corn Yield under Each Irrigation System for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

Thus it is not surprising that the present value of net revenues per hectare of irrigated corn production using SDI is $10,642, slightly less than with sprinkler irrigation which is $10,970 (Table 11). But when one considers that with center pivot irrigation, part of the quarter section must be in dry-land (which we assumed was planted with dry-land wheat) we obtain a different picture and that is that per hectare net revenues of center pivot irrigation are lowered to $9,118. Over the whole quarter section, cumulative net revenue for SDI is $666,555 and for center pivot irrigation is $572,174, a difference of over $95,000 dollars in favor of the SDI over the 100-year production horizon. Over the planning horizon, this corresponds to approximately $950/year. Under risk neutrality, a farmer will adopt the SDI system. This result is consistent with our initial hypothesis that over time SDI would be a more profitable technology despite the higher initial investment and management costs.

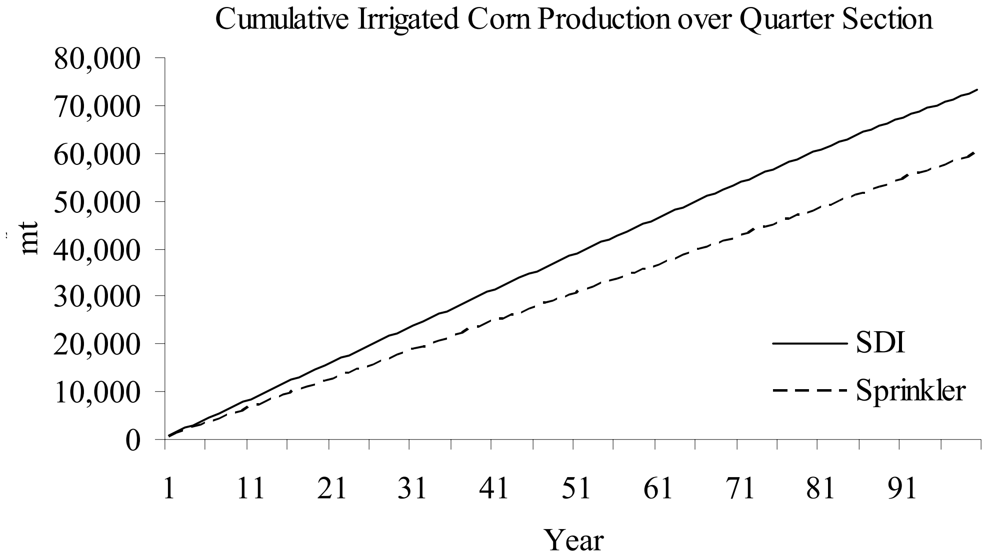


Figure 10. Projected Cumulative Irrigated Corn Production over the Quarter Section for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

Sensitivity Analysis for Deterministic Model Results

The sensitivity analysis of the above-described results was implemented by considering the effects of three different alternative scenarios for each irrigation system: 1) a drop in initial aquifer level of 50 percent, 2) an increase in the interest rate from 5 percent to 10 percent, and 3) an increase in the price of natural gas from $3.50 to $5 per 1000 cubic feet. Note that soil phosphorus and soil nitrogen are not measured after aquifer depletion, thus their level is set to the last measured level.

Table11.Summary Solution for Deterministic Model

		Irrigation System	
Variables	unit	Subsurface Drip Irrigation	Center Pivot Sprinkler Irrigation
Irrigation Level			
Annual average/irrigated area	mm/ha	413	469
Lifetime application to QS	m	2,590	2,394
Effluent Applied			
Annual average/irrigated area	kg/ha	194	298
Lifetime application to QS	mt	1,219	1,518
Soil Nitrogen			
Average over time and area	kg/ha	21	25
Soil Phosphorus			
Average over time and area	kg/ha	100	126
Corn Yield			
Annual average/irrigated area	mt/ha	11.66	11.73
Lifetime production of QS	mt	73,143	59,832
Net Present Value			
Average over irrigated area	$/ha	10,642	10,970
Average over all area	$/ha	10,642	9,118
Lifetime NR over QS	$	667,555	572,174

Notes: Unless otherwise noted, averages over area refer to averages taken over irrigated area (62.73 hectares for SDI and 50.99 hectares for center pivot). Irrigated land is cultivated with corn; dry-land is cultivated with wheat. Averages over time refer to averages taken over the production horizon, assumed to be 100 years.

Sensitivity Analysis for Subsurface Drip Irrigation

The increase of the price of natural gas from $3.50 to $5 per 1000 cubic feet extended the life of the aquifer (Figure 11) because, compared to the original solution, irrigation level was reduced in the first 62 years (Figure 12) to compensate for the higher cost of extracting water, thus allowing higher irrigation levels in the last years of the production horizon.

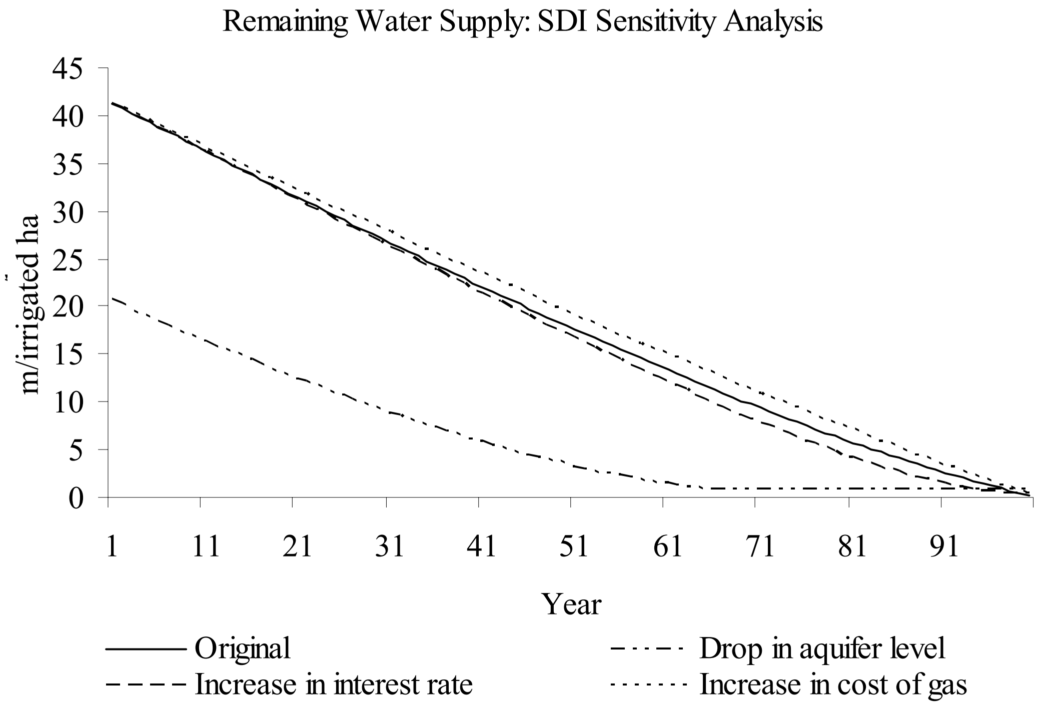


Figure 11. Sensitivity Analysis for Remaining Water Supply Using SDI to Produce Irrigated Corn for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

The inverse happens when the real discount rate increases: production in the near-future is more valuable than far-future production, thus it is preferable to irrigate more in early years and less toward the end of the production horizon (Figure 12). In fact, in our case, given our assumptions, the irrigated corn production horizon is shortened by four years and production is switched to dry-land wheat (Figure 13).

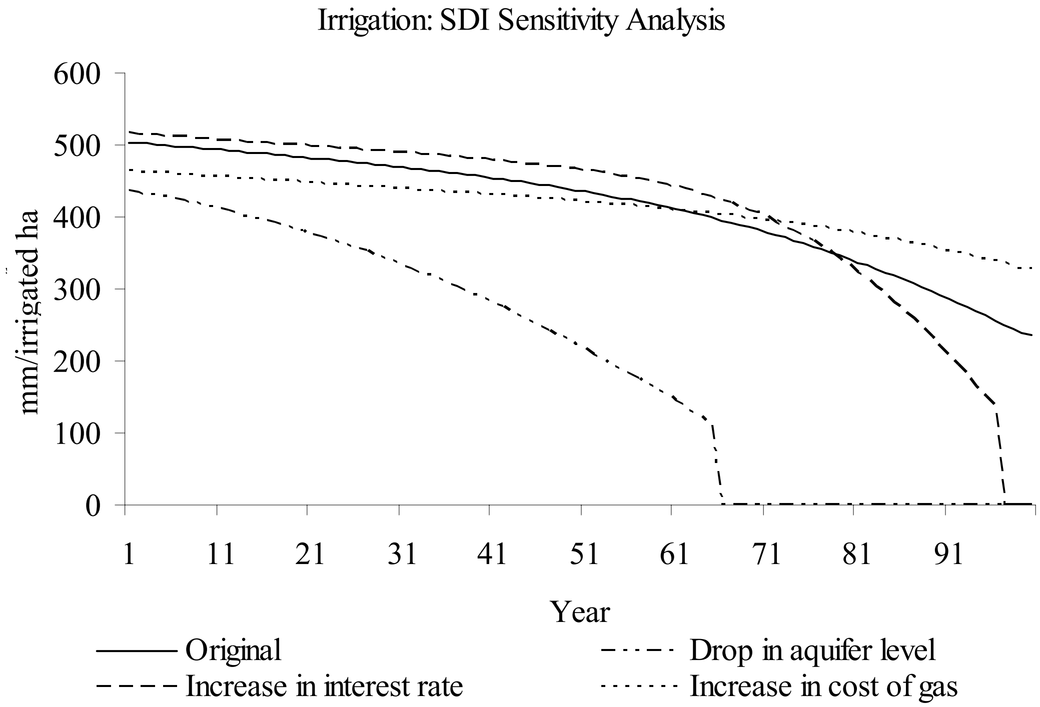


Figure 12. Sensitivity Analysis for Amount of Water Used in Irrigation under SDI to Produce Irrigated Corn for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

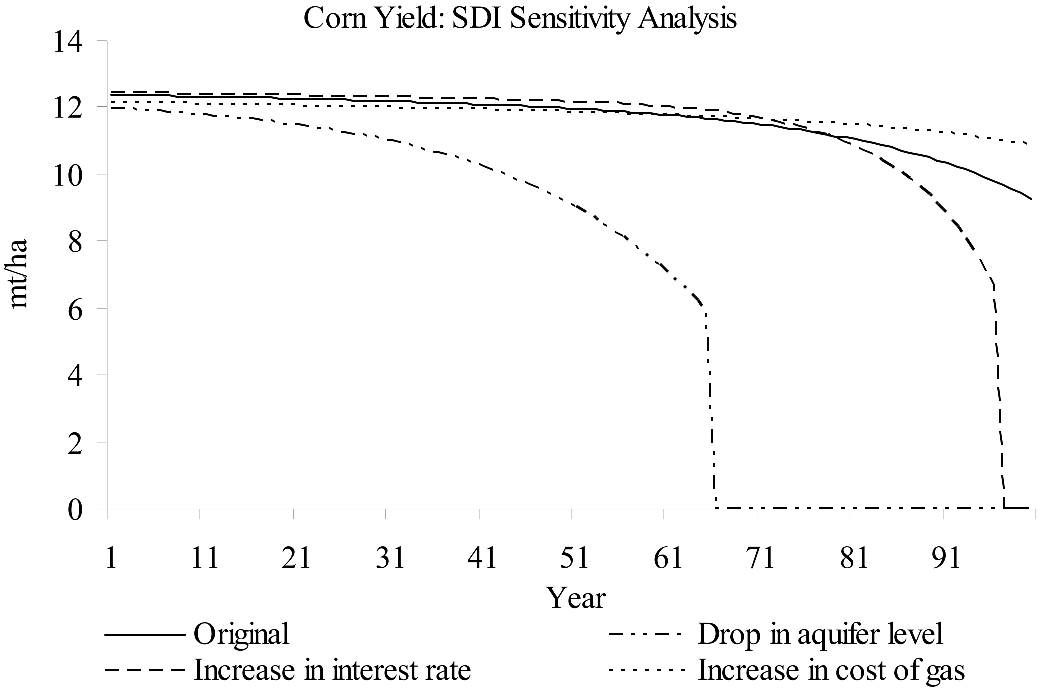


Figure 13. Sensitivity Analysis for Irrigated Corn Yield under SDI for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

Corn yield follows the evolution of irrigation and remaining water supply pretty closely, given the three scenarios. Under the water table decline scenario, the production horizon of irrigated corn is shortened by 35 years. Near-future corn production is sacrificed in favor of far-future production given the increase in the cost of natural gas and vice-versa given the increase in the interest rate (Figure 13).

Effluent application is closely related to irrigation, thus whenever irrigation becomes economically infeasible, so does effluent application to soil. Thus effluent application is severely limited by a decline in the amount of extractable water in the aquifer (Figure 14).

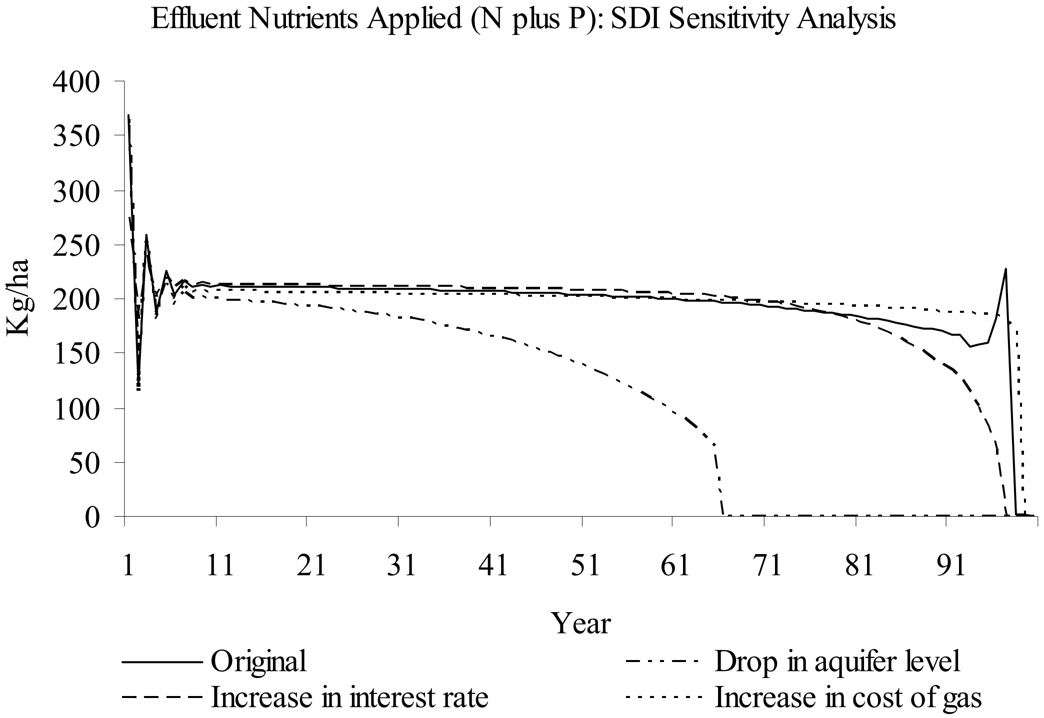


Figure 14. Sensitivity Analysis for Level of Effluent Nutrients Applied (Nitrogen plus Phosphorus) to Irrigated Corn under SDI for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

The initial instability in the level of effluent applied reflects that initial starting values for the optimization were too high and adjustments were made until a stable level was found. During the first 80 years, this level was very close for the flowing scenarios: original, increase in interest rate, and increase in cost of natural gas; differences became more noticeable later in the production horizon (Figure 14).

The evolution of soil nutrients over the production horizon reflects the balance (or lack of it) between nutrient removal due to corn production, runoff (in the case of phosphorus, leaching, percolation (these last two in the case of nitrogen), etc. and nutrient addition due to effluent application. If nutrient removal and addition are about the same, then soil nutrient is kept at a pretty constant level. During most of the production horizon, soil nitrogen is very stable indicating a balance between removal and addition of nitrogen to soil (Figure 15).

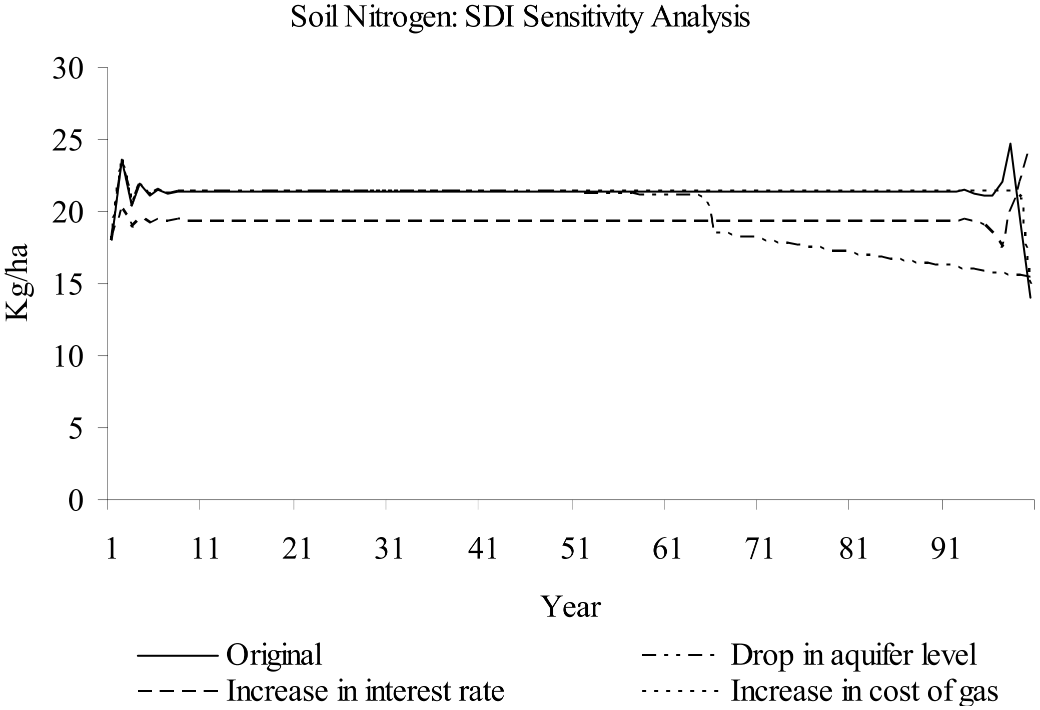


Figure 15. Sensitivity Analysis for Soil Nitrogen under SDI to Produce Irrigated Corn for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

Some things should be pointed out: first, given an increase in the interest rate, less nitrogen is in the soil compared to the other scenarios; second, given an increase in the cost of natural gas, the level of soil nitrogen is not greatly affected compared to the original scenario; third, a decline in the water table only affects the balance of soil nitrogen after irrigation becomes infeasible.

Soil phosphorus accumulation always occurs whenever effluent is being applied to the soil for all scenarios (Figure 16). An increase in the interest rate or an increase in the cost of natural gas has little impact on soil phosphorus compared to the original scenario. On the other hand, the scenario where we assumed a decline in aquifer water first allows soil phosphorus to increase at a lower rate, until effluent is no longer applied. At that point soil phosphorus actually declines.

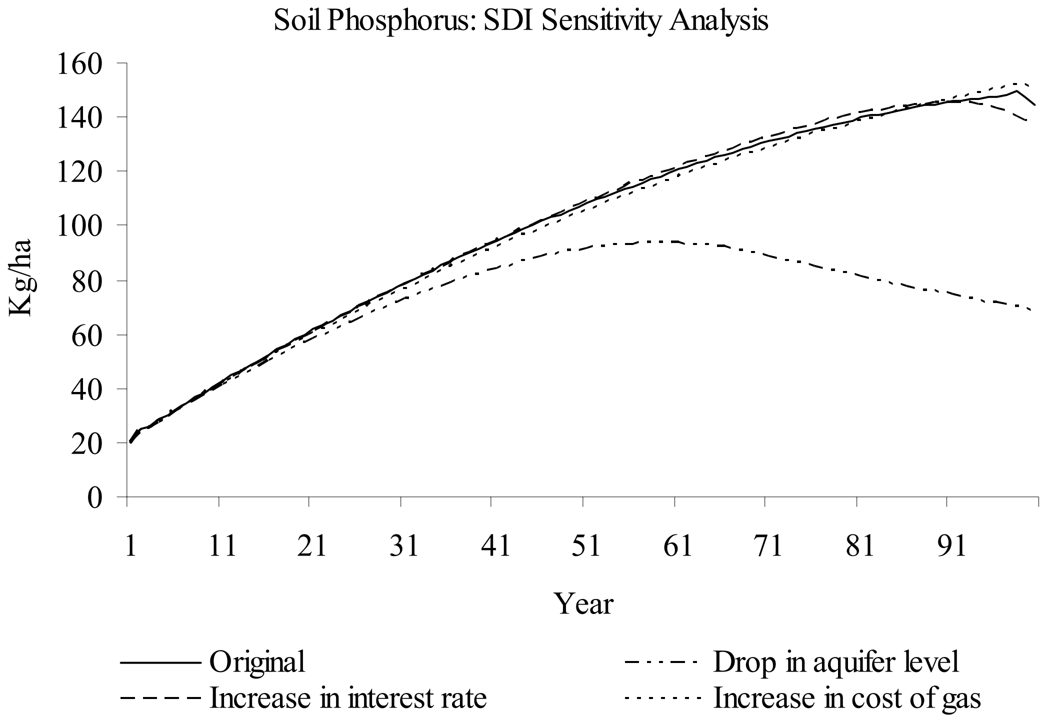


Figure 16. Sensitivity Analysis for Soil Phosphorus under SDI to Produce Irrigated Corn for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

Sensitivity Analysis for Center Pivot Sprinkler Irrigation

While there is not much difference in remaining water supply between the original scenario and the scenario where we assume an increase in the interest rate, the increase in the cost of natural gas, extends aquifer life as more water is left in the aquifer at the end of the production horizon. As expected, a lower initial level in the water table cuts down the production horizon of irrigated corn (Figure 17).

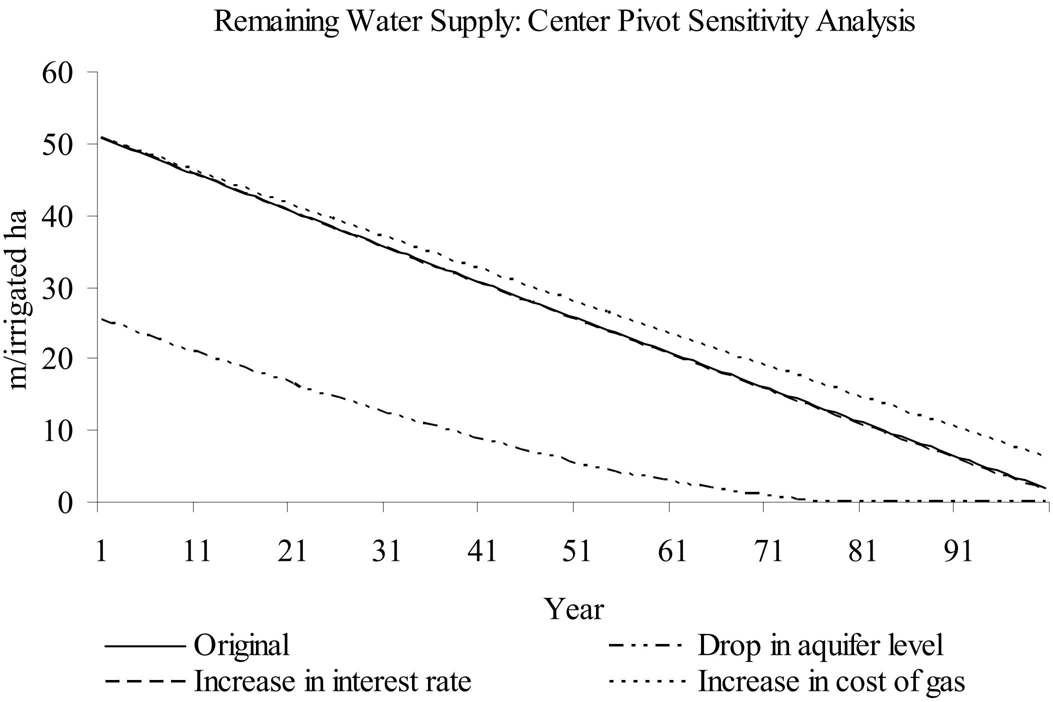


Figure 17. Sensitivity Analysis for Remaining Water Supply for Quarter Section Using Center Pivot Sprinkler Irrigation to Produce Irrigated Corn for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

The change in remaining water in aquifer is a direct reflection of the irrigation level. The increase in the price of natural gas, which increases the cost of extracting groundwater, reduces the irrigation level about 50 mm/ha throughout the production horizon compared to the original scenario (Figure 18), thus more water is left at the end of the 100-year production horizon.

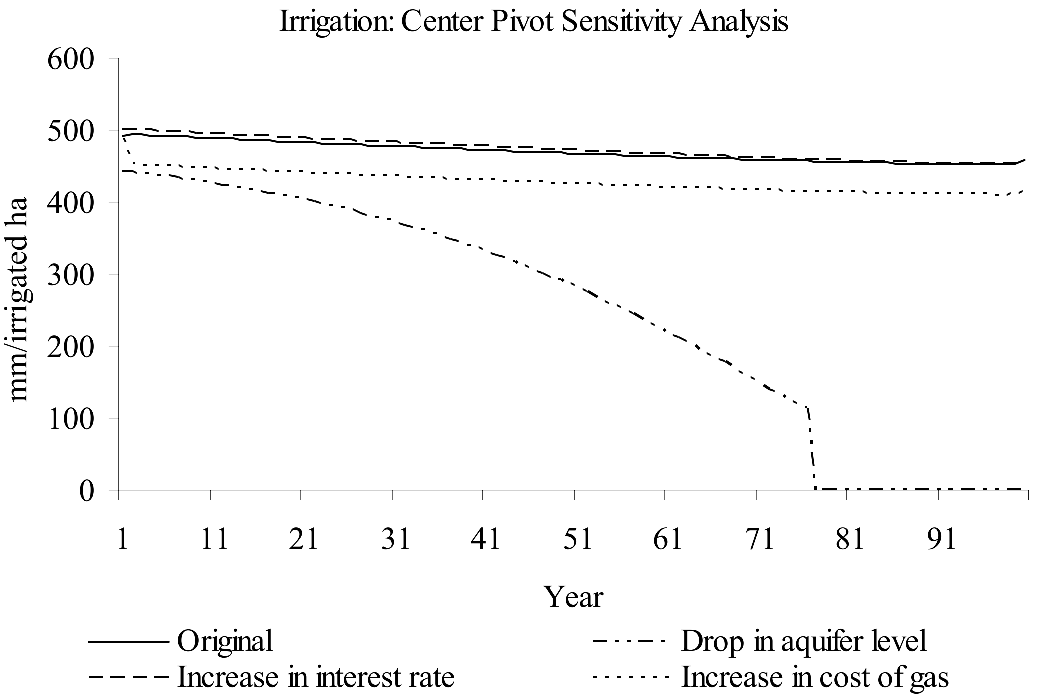


Figure 18. Sensitivity Analysis for Amount of Water Used in Irrigation under Center Pivot Irrigation to Produce Irrigated Corn for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

Despite the reduction in irrigation, given the increase in the cost of natural gas, the reduction in yield was only about 0.2 metric tons over the production horizon (Figure 19). The trade-off between current production and future production was not that significant for center pivot irrigation. Under the scenario where the initial water table level was reduced by 50 percent, the production horizon of irrigated corn was shortened by 24 years, a lot less than for SDI. Serious implications for feasibility of effluent application over time occur under the scenario where the water table level is cut in half. For the other scenarios, there is not much difference from the original scenario (Figure 20).

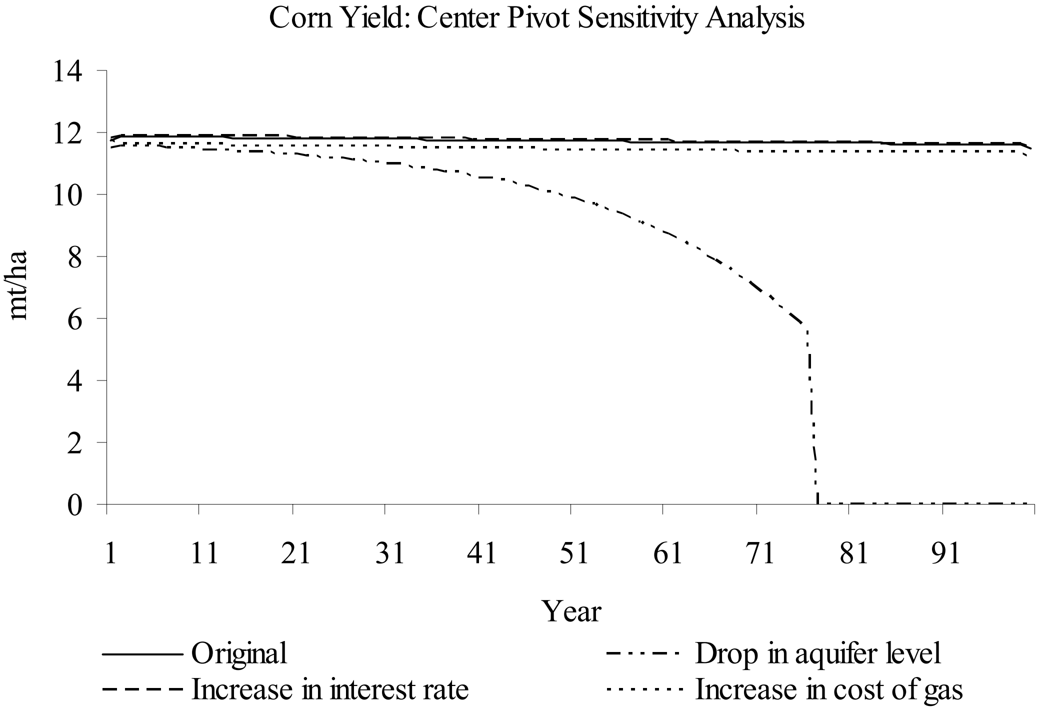


Figure 19. Sensitivity Analysis for Irrigated Corn Yield under Center Pivot Irrigation for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

Soil nitrogen also is very stable under the SDI except for the scenario where the initial aquifer level was cut in half. Under the scenarios where there is an increase in the cost of natural gas and an increase in the discount rate, soil nitrogen is approximately 3 kg/ha lower than under the original scenario (see Figure 21).

Soil phosphorus increases over time due to effluent application. The level of soil phosphorus is lower under the scenarios where initial aquifer level was reduced and cost of natural gas was increased. The increase in the interest rate, as discussed before, did not have much effect on effluent applied and irrigation level, thus yield was also affected minimally and we can observe that there is little effect to no effect in soil phosphorus in this scenario compared to the original scenario (Figure 22).

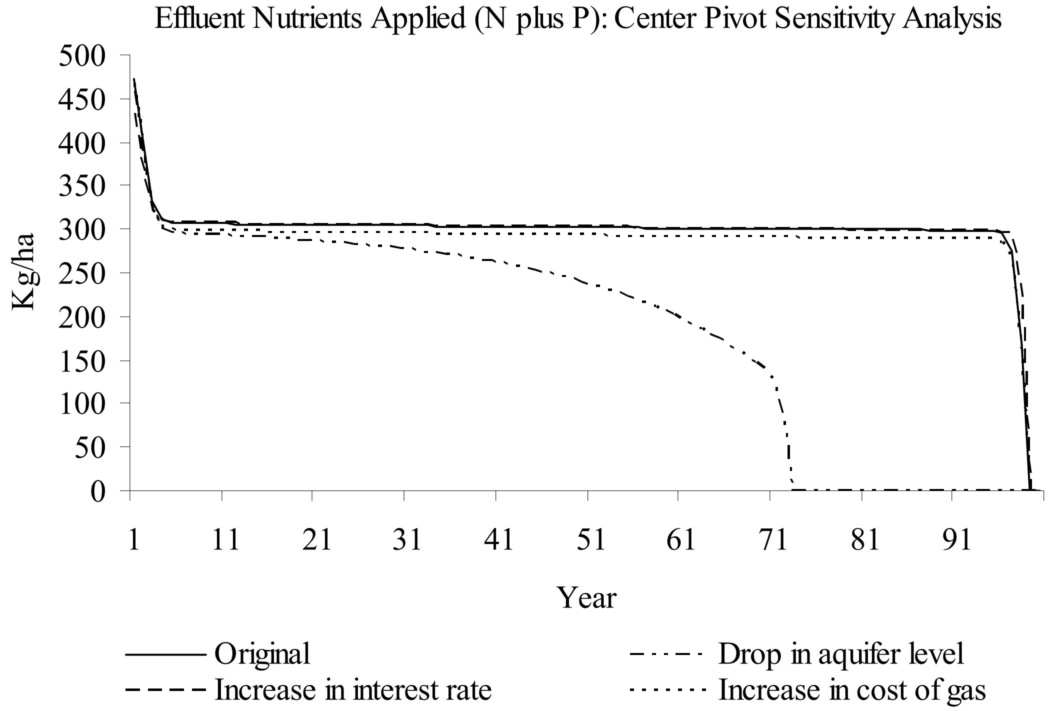


Figure 20. Sensitivity Analysis for Level of Effluent Nutrients Applied (Nitrogen plus Phosphorus) to Irrigated Corn under Center Pivot Irrigation for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

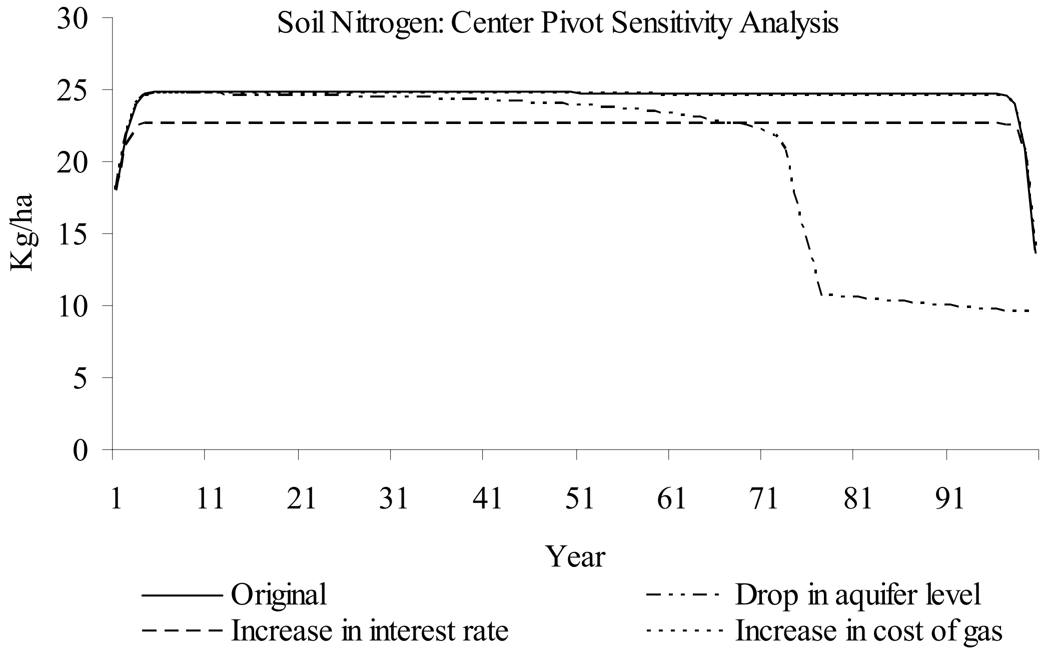


Figure 21. Sensitivity Analysis for Soil Nitrogen under Center Pivot Irrigation to Produce Irrigated Corn for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

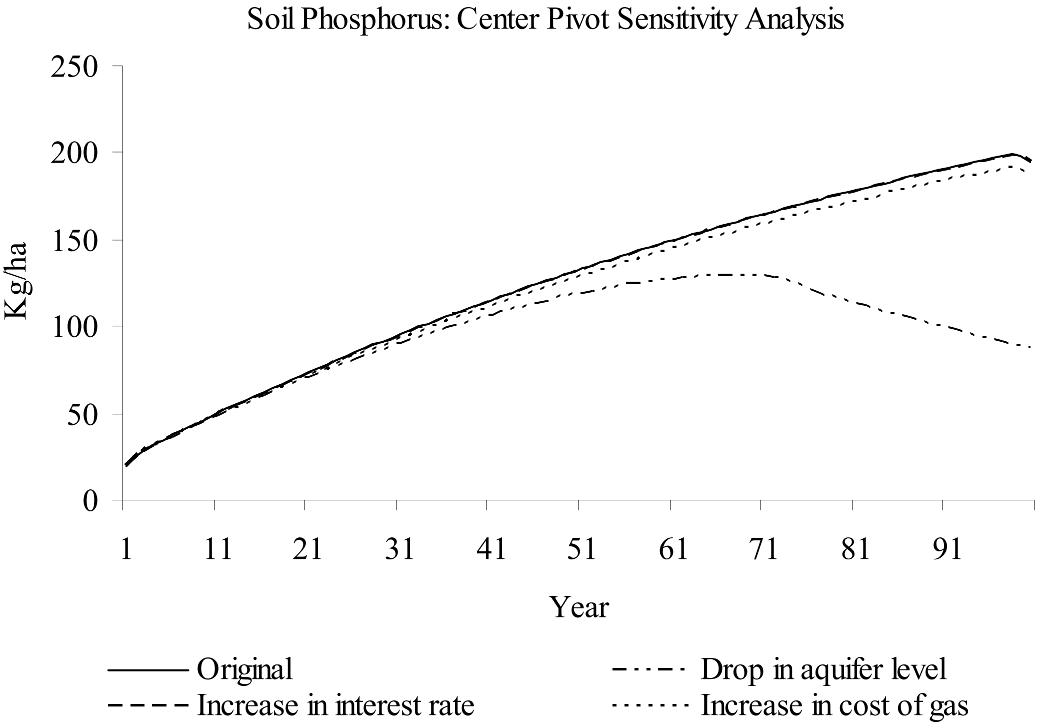


Figure 22. Sensitivity Analysis for Soil Phosphorus under Center Pivot Irrigation to Produce Irrigated Corn for the 100-Year Production Horizon Using the Deterministic Optimization Procedure

Sensitivity Analysis: Economic Implications

A summary of the sensitivity analysis is presented in Table 12. The conclusions of the model for each irrigation system are most sensitive to drastic changes in the amount of water available for irrigation in aquifer, which is scenario II. Decreasing the water supply by half negatively affects both monetary and physical variables. Declines in water supply reduce profitability of both irrigation systems. However, they do not affect the previous conclusion that the SDI performs better than the center pivot in terms of net revenues over long periods of time and under land and water constraints. Obviously, an increase in the interest rate also has significant monetary effects for both systems as such a change reduces the value of future net revenue in the discounting process.

For the SDI, the consequences of an increase in the interest rate (scenario III) or an increase in the cost of natural gas (scenario IV) have little effect on the physical variables soil nitrogen, soil phosphorus, effluent applied and irrigation applied compared to the original scenario; in terms of average yield, scenario III underperforms by about 0.5 tons/acre on average compared to the original scenario—this translates into a three ton difference over time. For center pivot sprinkler irrigation, there is little difference between the physical results of scenario III and those of the original scenario. An increase in the cost of natural gas has a greater impact for this system which may be due to the fact that the center pivot ends up using more water, thus it is more susceptible to an increase in the water extraction costs.

Table 12.Summary and Economic Implications of Sensitivity Analysis for Deterministic Model

		Irrigation System & Scenario							
		Subsurface Drip Irrigation				Center Pivot Sprinkler Irrigation			
Variables	unit	Original	½ W_{Sup}	r=10%	$P_{nat.gas}=\$5$	Original	½ W_{Sup}	r=10%	$P_{nat.gas}=\$5$
Irrigation Level									
Irrigation life	years	100	65	96	100	100	76	100	100
Annual average/irrigated area	mm/ha	413	306	426	413	469	318	473	427
Lifetime application to QS	m	2,590	1,248	2,565	2,590	2,394	1,233	2,410	2,179
Effluent Applied									
Annual average/irrigated area	kg/ha	194	167	196	197	298	254	297	288
Lifetime application to QS	mt	1,219	681	1,181	1,233	1,518	931	1,517	1,471
Soil Nitrogen									
Average over time and area	kg/ha	21	20	19	21	25	20	22	22
Soil Phosphorus									
Average over time and area	kg/ha	100	73	100	99	126	96	125	122
Corn Yield									
Annual average/irrigated area	mt/ha	11.66	10.26	11.64	11.77	11.73	10.02	11.74	11.45
Lifetime production of QS	mt	73,143	41,823	70,109	73,824	59,820	38,825	59,870	58,408
Net Present Value									
Average over irrigated area	$/ha	10,642	8,728	4,723	9,468	10,970	9,750	5,586	9,870
Average over all area	$/ha	10,642	8,728	4,723	9,468	9,118	6,088	3,506	6,162
Lifetime NR over QS	$	667,555	565,152	305,863	593,886	572,174	509,757	297,440	515,838

Notes:

The four scenarios considered are i. original scenario; ii. reduction of initial water supply/aquifer level by 50 percent; iii. increase in real discount rate from 5 to 10 percent; and iv. increase in cost of natural gas from $3.50 to $5 per 1000 cubic feet.

Unless otherwise noted, averages over area refer to averages taken over irrigated area (62.73 hectares for SDI and 50.99 hectares for center pivot).

Averages over time refer to averages taken over the production horizon, assumed to be 100 years or the irrigation life, whichever one is shortest.

Irrigated land is cultivated with corn, until aquifer becomes economically depleted; dry-land is cultivated with wheat.

Stochastic Dynamic Optimization with Risk Aversion Results

Ammonia Volatilization PDF Parameter Estimates

The stochastic analysis uses ammonia volatilization as an additional source of randomness. A probability distribution function with a closed form CDF was developed for the variable ammonia volatilization as described in the previous chapter and in Appendix D. Recall that this probability distribution has the advantage of allowing the probabilities to change according to the level of nitrogen applied to irrigated corn. The parameters of this PDF were estimated in SAS with procedure NLMIXED for each irrigation system, with the data simulated in EPIC. The results for this estimation, presented in Table 13, conform to the requirements for a PDF, mainly that parameter ρ_1 must be positive, while ρ_2 must be negative, in order for the PDF to integrate to one.

Table 13 Parameter Estimates for Ammonia Volatilization PDF Computed in SAS Procedure NLMIXED

Variable	Symbol	Parameter Estimates SDI	 Center Pivot
Intercept	ρ_0	-0.4795	0.7553
		(-3.67)	(5.96)
Ammonia volatilization	ρ_1	1.8935	0.4618
		(70.11)	(68.25)
Inverse of ammonia volatilization	ρ_2	-3.2854	-10.7084
		(-4.87)	(-6.52)
Effluent nitrogen	ρ_3	-0.1541	-0.1120
		(-70.89)	(-70.54)
Urea	ρ_4	-0.1902	-0.0775
		(-70.98)	(-70.15)

Notes: All parameters are statistically significant at the 5 percent significance level. Approximate t-values reported in parentheses. N=3,780.

The above parameters imply that ammonia volatilization is greater for center pivot sprinkler irrigation compared to SDI and that the variance of ammonia volatilization for center pivot is also greater than that of SDI (Figure 23).

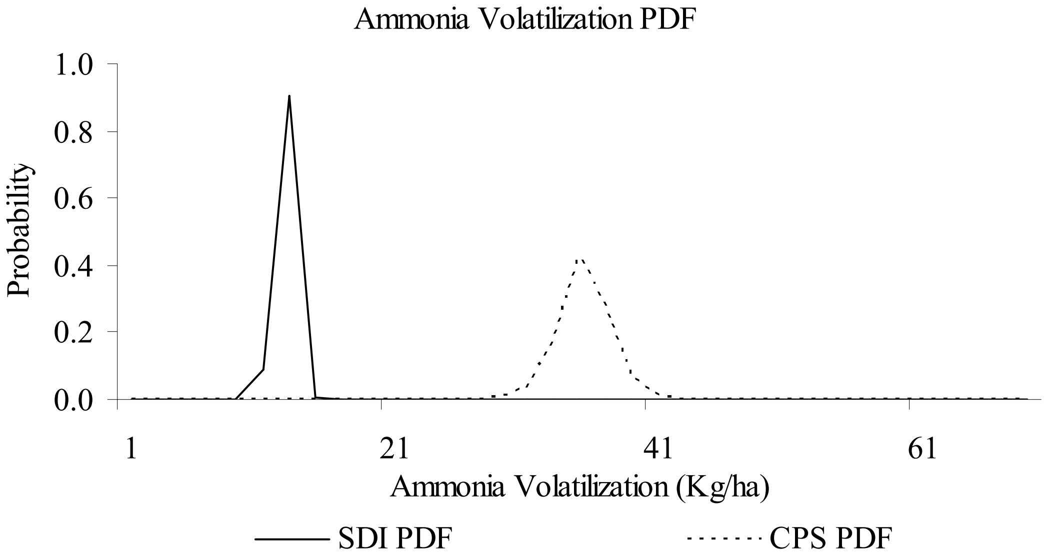


Figure 23. Illustration of Each Irrigation System's Ammonia Volatilization PDF Given an Effluent Application of 150 kg/ha

Figure 23 illustrates the two probability distributions of ammonia volatilization given an application of effluent nitrogen of 150 kg/ha. The higher variance of the center pivot sprinkler irrigation system can be identified intuitively by how much wider the distribution for this system is compared to the distribution for the SDI. In fact the distribution for the SDI is quite tall and concentrated around the mean. Variance is important as higher variance is associated with higher risk. Also worth mentioning is the fact that the two probability distributions are not symmetric although they are bell-shaped.

The objective of the stochastic model is to maximize expected utility of present wealth and future net returns from growing irrigated corn given the constrained water supply. The utility function used in the analysis is a power function, which was defined in a prior section. The results obtained are consistent with the deterministic results but since the producer is risk averse, more water is used in irrigation as a risk-minimizing strategy. Figure 24 illustrates the projected amount of water used in irrigation under each system. For the first 86 years, both systems use similar irrigation amounts. The center pivot sprinkler used slightly more water but a portion of that water is lost to evaporation, which we assume is 5 %. While in the deterministic model, the optimal amount of water used in irrigation with the SDI declined steadily (refer back to Figure 3) over the 100-year period, in the stochastic model the water amount is held roughly at the same level until the aquifer is economically exhausted (Figure 24) around year 86, i.e., the cost of extracting an additional unit of water exceeds the revenue from utilizing that water. Once again recall that with the SDI, a greater area is being irrigated and planted to corn.

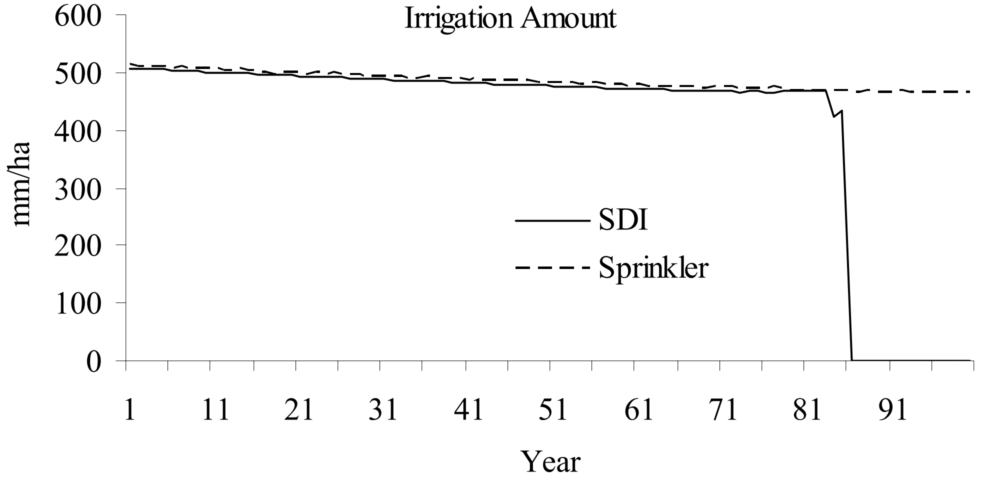


Figure 24. Projected Amount of Water Used in Irrigation of Corn by Each Irrigation System for the 100-Year Production Horizon Using the Stochastic Optimization Procedure Assuming the Quarter Section Has 323 ha of Aquifer Available for Water Extraction with Each Hectare Having 16.15 m of Water-Saturated Sand with 15% Aquifer Specific Yield

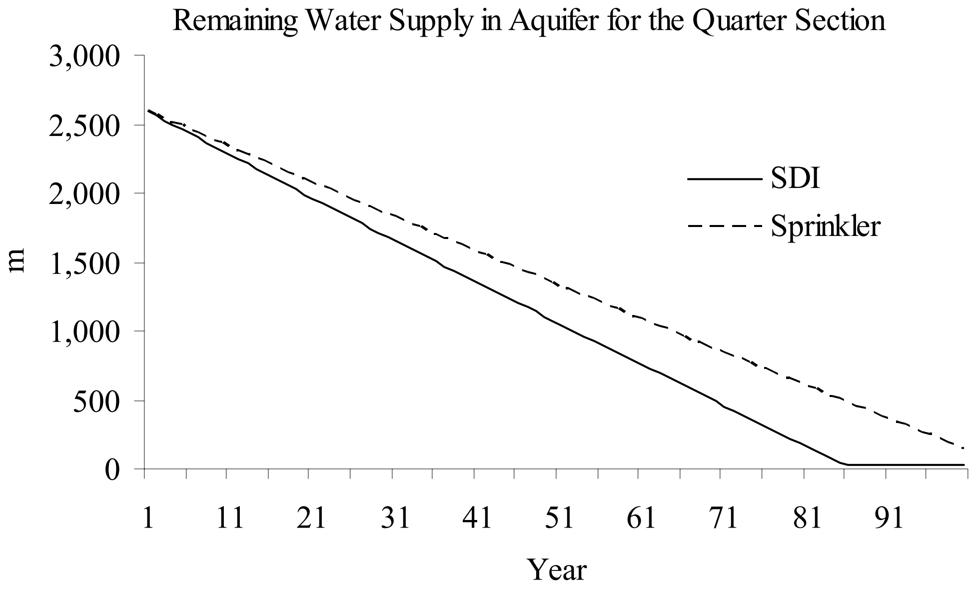


Figure 25. Projected Amount of Remaining Water in Aquifer for Quarter Section for Each Irrigation System for the 100-Year Production Horizon Using the Stochastic Optimization Procedure Assuming the Quarter Section Has 323 ha of Aquifer Available for Water Extraction with Each Hectare Having 16.15 m of Water-Saturated Sand with 15% Aquifer Specific Yield

In terms of amount of water available per irrigated hectare, the SDI has less water that the center pivot sprinkler and over the course of the 100-year planning horizon, the SDI exhausts the water supply faster than the CPS (Figure 26) because with the SDI a greater area is irrigated.

In terms of effluent applied as nitrogen and phosphorus, less effluent is applied with the SDI than with the CPS on a per-hectare basis (Figure 27). Compared to the deterministic solution, the optimal application level for the SDI increased and was kept around 260 kg/ha—it used to be around 200 kg/ha. In the stochastic program, the amount of effluent applied is not a continuous variable. Consequently, and given the increased ammonia volatilization uncertainty associated with the CPS, the effluent application level is not as smooth as in the deterministic model, , which implies that because the center pivot sprinkler is riskier in terms of variance of yield resulting from the greater variance of ammonia volatilization, the management strategy used (amount of irrigation and effluent applied) should be more flexible, thus more variability can occur in the level of irrigation and effluent applied from year to year. The SDI because it is less susceptible to ammonia volatilization uncertainty does not exhibit this problem.

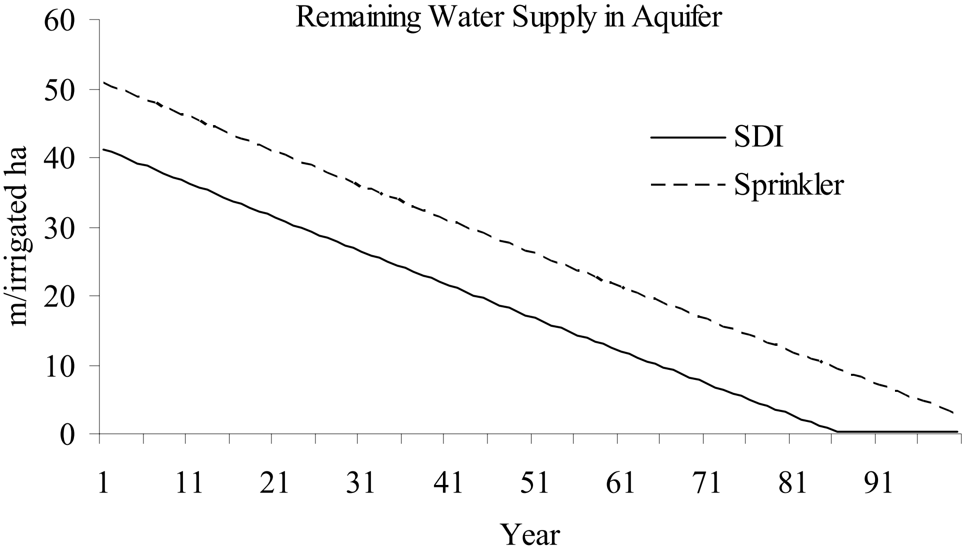


Figure 26. Projected Amount of Remaining Water in Aquifer per Irrigated Hectare for Each Irrigation System for the 100-Year Production Horizon Using the Stochastic Optimization Procedure Assuming the Quarter Section Has 323 ha of Aquifer Available for Water Extraction with Each Hectare Having 16.15 m of Water-Saturated Sand with 15% Aquifer Specific Yield

The accumulation of nitrogen in the soil projected for the stochastic model is illustrated in Figure 28. More nitrogen accumulates in the soil with the CPS because more effluent is applied and corn yield is lower than with the SDI (Figure 30), thus more removal is projected to occur under the latter irrigation system. The accumulation of phosphorus in the soil also occurs faster with the center pivot sprinkler system than with the SDI because less effluent is applied with the SDI and greater yield removal occurs (Figures 29 and 30). After depletion occurs, the level of soil nutrients is assumed to be constant, although in actuality, some removal could occur if the dry-land wheat was grazed or cut and removed from the field.

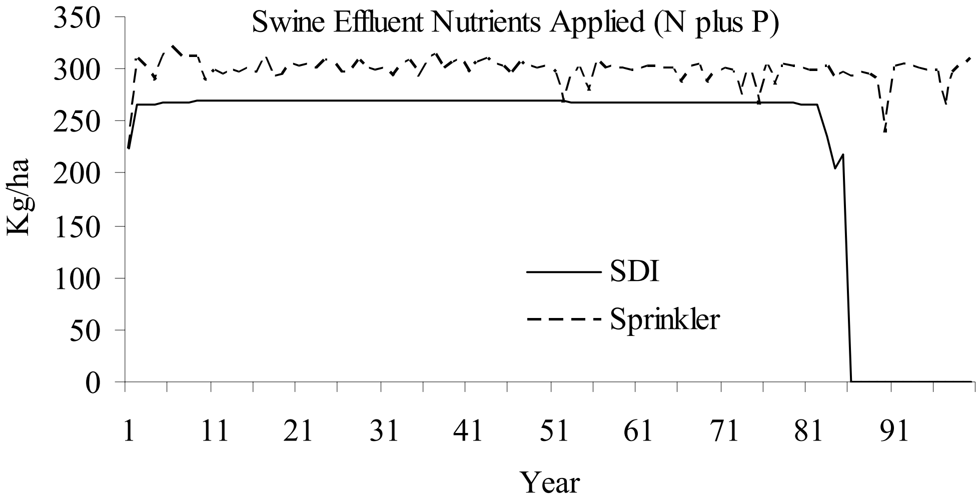


Figure 27. Projected Amount of Swine Effluent Nutrients Applied (Nitrogen plus Phosphorus) under Each Irrigation System for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

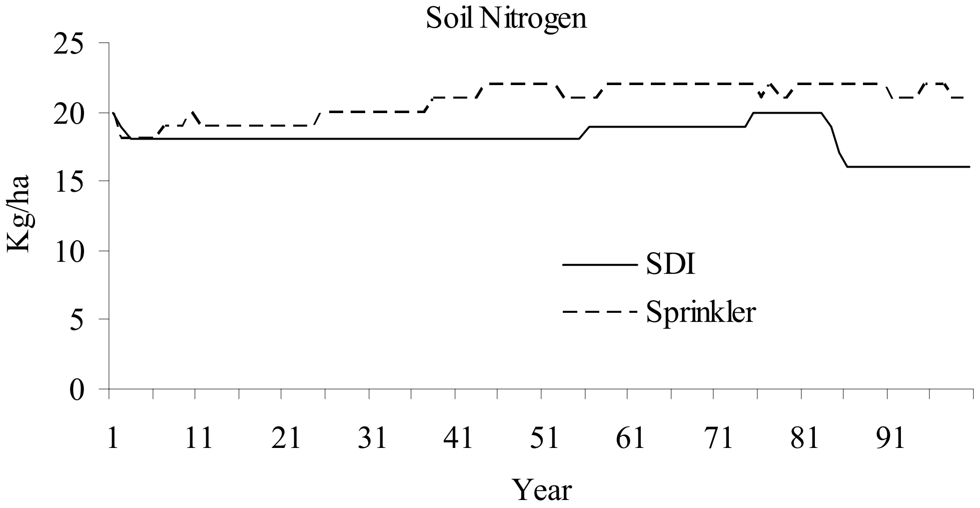


Figure 28. Projected Accumulation of Nitrogen in Soil under Each Irrigation System for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

Compared to the deterministic solution, the total amount of effluent applied under the SDI increases from 1,219 mt to 1,420 mt; for the center pivot the increase is negligible: from 1518 mt to 1520 mt. A possible explanation for this result has to do with what happens to the total amount of water used for irrigation over the production horizon. For the SDI the total amount of water used in irrigation over the production horizon declines from 2,590 to 2,568 m; for the CPS the total amount of water used in irrigation increases from 2,394 m to 2468 m. In the SDI, water is a binding constraint as the aquifer is economically depleted by year 86. Increasing the amount of water applied could have hastened economic depletion, thus it may be preferable to increase effluent application since there is no constraint on effluent.

For the first 86 years, the stochastic model predicts higher irrigated corn yields with the SDI than with the CPS both on a per hectare basis and cumulatively over the quarter section, a result that is consistent with the deterministic model. However, in year 86, with the SDI, economic exhaustion of the aquifer occurs and from then on, the quarter section reverts to the production of dry-land wheat (Figure 30). The pertinent issue is whether the initial higher yield is enough to compensate for the shorter production period of corn for the SDI. The answer to this question is yes as can be seen in Figure 31, which illustrates the predicted cumulative yield per hectare under both systems over the 100-year period. Besides the SDI having a greater yield on a per-ha basis, the difference in cumulative yield is even more marked because over the quarter section the SDI allowed more area to be cultivated with irrigated corn.

A summary comparison of both systems for the stochastic dynamic analysis is presented in Table 14. The stochastic analysis results are consistent with the deterministic analysis results and with our initial hypothesis that the SDI would be a more profitable irrigation system compared to the center pivot sprinkler. The advantage of the SDI is $37,578 over the 100-year period, which is not a very significant difference annually.

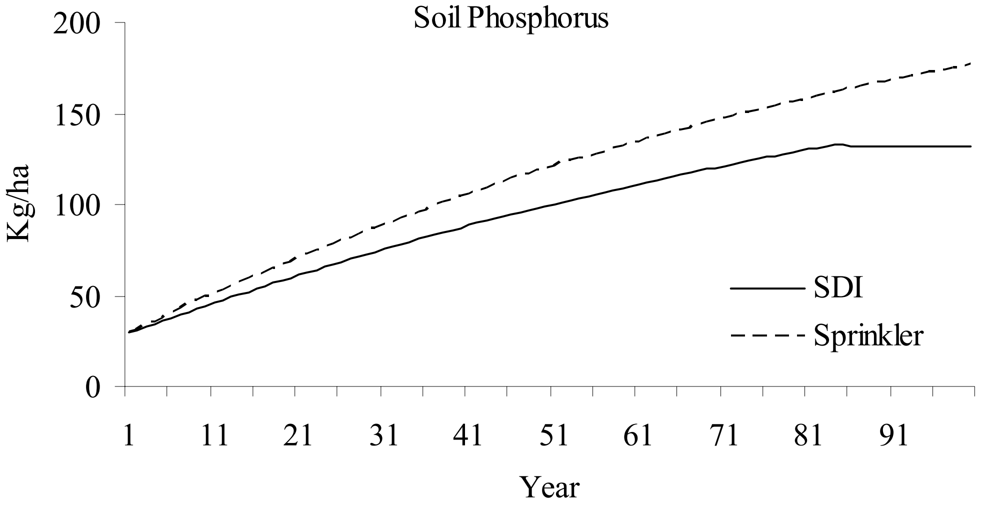


Figure 29. Projected Accumulation of Soil Phosphorus under Each Irrigation System for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

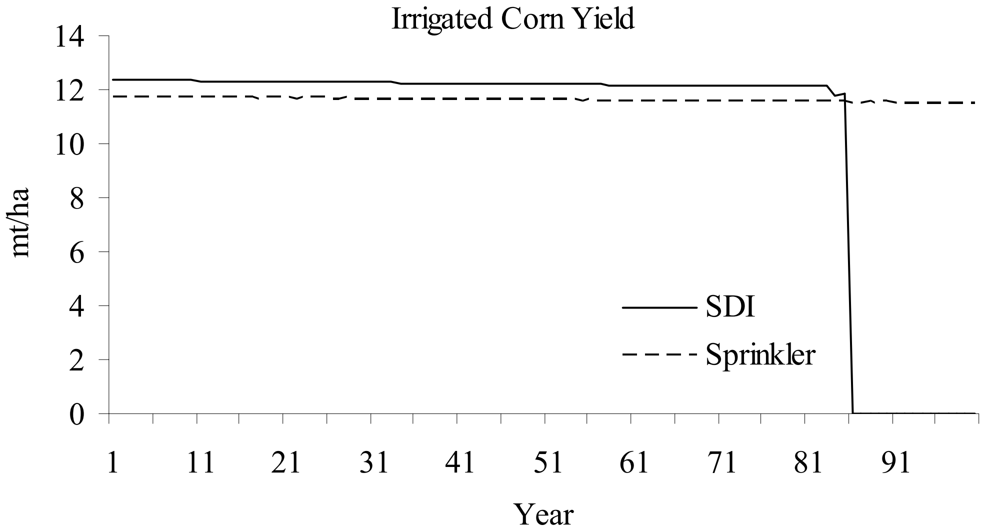


Figure 30. Projected Irrigation Corn Yield under Each Irrigation System for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

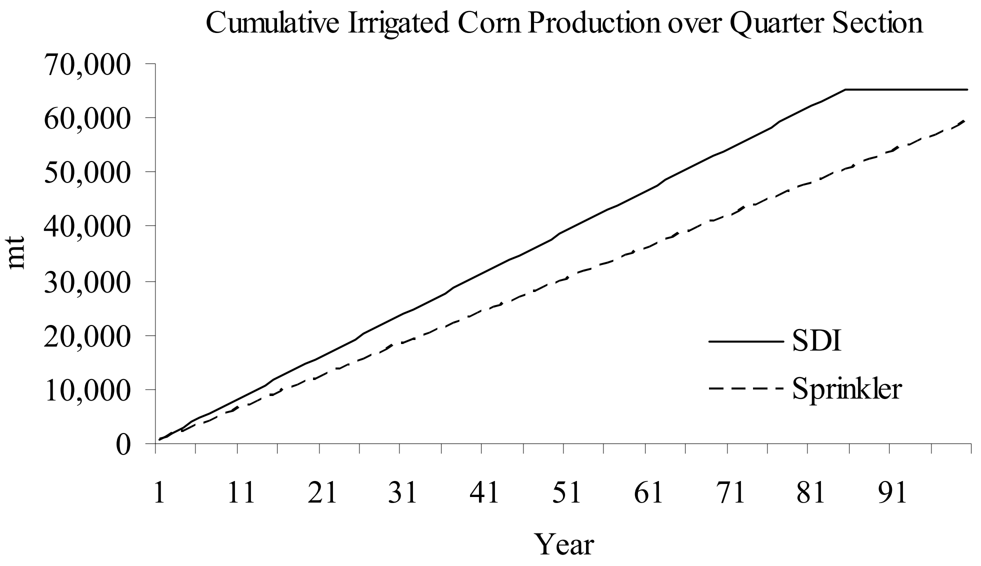


Figure 31. Projected Cumulative Irrigated Corn Production over the Quarter Section for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

In the deterministic optimization the difference in the NPV of the expected net returns over the 100-year production horizon had been over $90,000 in favor of the SDI. The inclusion of risk decreases the advantage of the SDI. The main reason behind it is that since a greater portion of land is irrigated under the SDI than under the Center Pivot Sprinkler, the adoption of dry-land wheat occurs earlier in the SDI because the aquifer is depleted faster. Because in the stochastic model we assume a risk-averse individual, more irrigation is used per ha (476 mm is the average over the 86 years that the quarter section is irrigated) compared to the level that would have been used under risk neutrality (413 mm, from the deterministic solution).

An interesting fact that is sometimes overlooked is that under the SDI, the variance of the total irrigated corn area is 3,995 greater than the variance per irrigated ha of producing irrigated corn with the SDI; under the center pivot, the variance of the total rrigated corn area is only 2,600 greater than the variance per ha of using the CPS to produce corn. Thus there is definitely a trade-off, on any year, between the lower per ha variance of the SDI and its greater aggregate variance. In terms of dry-land wheat, more area is cultivated under the CPS, if there is irrigated corn being produced, thus the aggregate variance of dry-land wheat is greater for this system. But if under the SDI depletion occurs earlier, as was the case in this study, then during the last years of the production horizon, more area is under dry-land wheat with the SDI than with the CPS. If the probability distributions are symmetric around the mean, and there is risk neutrality, the system with the highest mean net revenue will prevail. If there is risk aversion then the analysis becomes much more complicated and the outcome may not be as intuitive.

Table 14. Summary Solution for Stochastic Model

		Irrigation System	
Variables	unit	Subsurface Drip Irrigation	Center Pivot Sprinkler Irrigation
Irrigation Level			
Annual average/irrigated area	mm/ha	482	484
Lifetime application to QS	m	2,568	2,468
Irrigation life	years	85	100
Effluent Applied			
Annual average/irrigated area	kg/ha	266	298
Lifetime application to QS	mt	1,420	1,520
Soil Nitrogen			
Average over time and area	kg/ha	19	21
Soil Phosphorus			
Average over time and area	kg/ha	88	114
Corn Yield			
Annual average/irrigated area	mt/ha	12.2	11.6
Lifetime production of QS	mt	65,191	59,191
Net Present Value			
Lifetime Expected Net Revenue	$	512,026	474,448
Lifetime Certainty Equivalent	$	511,702	474,122

Notes: Unless otherwise noted, averages over area refer to averages taken over irrigated area (62.73 hectares for SDI and 50.99 hectares for center pivot). Irrigated land is cultivated with corn; dry-land is cultivated with wheat. Averages over time refer to averages taken over the production horizon, assumed to be 100 years or the irrigation life, whichever one is shortest.

Sensitivity Analysis for Stochastic Model Results

Similarly to the sensitivity analysis conducted for the deterministic optimization results, the same will be done for the stochastic model results. The alternative scenarios considered are still the same as before: reduction of initial water supply in the aquifer by 50 percent; increase in real discount rate from 5 to 10 percent; and increase in cost of natural gas from $3.50 to $5 per 1000 cubic feet.

Sensitivity Analysis for Subsurface Drip Irrigation

Increasing the cost of natural gas increases the cost of pumping water from the aquifer and could be seen as a factor that contributes to water conservation. In the comparison of all scenarios, increasing the cost of natural gas not only postponed the economic exhaustion of the aquifer, but it also left more water remaining in the aquifer (Figure 32), an effect that had not been clear from the deterministic solution.

An increase in the discount rate had little resulted in almost no difference from the original results in terms of what happened to the remaining water supply. Decreasing the initial water supply by half hastens the economic exhaustion of the aquifer which occurs around year 44 instead of year 86. These results are also visible in Figure 33, which illustrates the level of irrigation used. The most interesting result from this figure, which was not noticeable in Figure 32, is that even with half of the initial water supply, the average level of irrigation is higher than with scenario with the higher cost of natural gas.

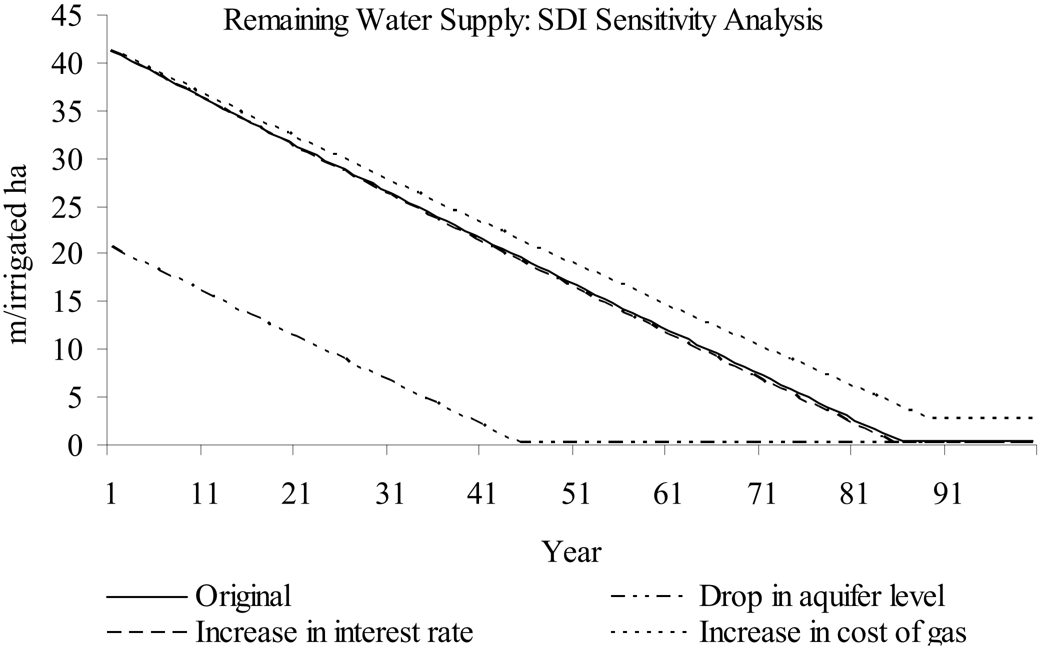


Figure 32. Sensitivity Analysis for Remaining Water Supply Using SDI to Produce Irrigated Corn for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

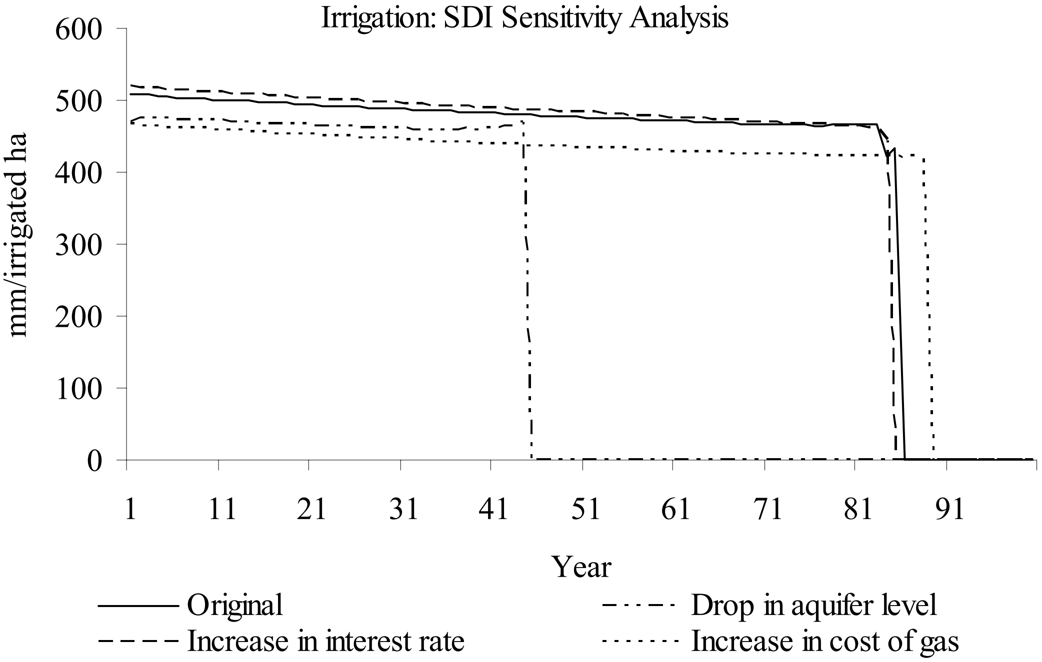


Figure 33. Sensitivity Analysis for Amount of Water Used in Irrigation under SDI to Produce Irrigated Corn for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

Rationally, water will be extracted if its marginal value exceeds the marginal cost of extracting an additional unit. Under risk aversion, more water will be used than under risk neutrality as a form of "insurance against risk"—recall that the variance of irrigated yield is assumed to decrease with irrigation. Thus a rational producer, that is risk averse, must consider whether the cost of extracting an additional unit of water outweighs the marginal benefits derived from increasing yields and the marginal benefits from decreasing yield variance. Further more, in a dynamic set-up, a rational producer must also consider whether the marginal benefit of water today is greater than the marginal benefit of water in the future. It is rational that an increase in the cost of extracting water will decrease its use over time.

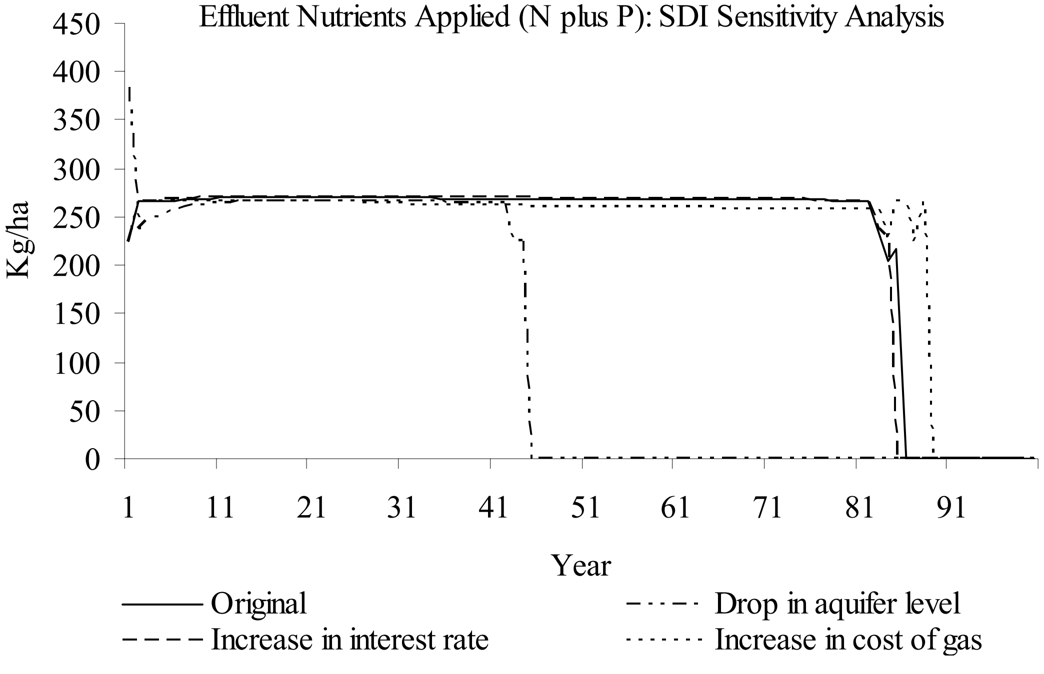


Figure 34. Sensitivity Analysis for Level of Effluent Nutrients Applied (Nitrogen plus Phosphorus) to Irrigated Corn under SDI for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

The optimal use of effluent, given the four scenarios considered, is reported in Figure 34. Effluent use is very similar for all scenarios considered.

In terms of corn yield, under all scenarios, when irrigation occurs, the expected yield is above 12 mt/ha (Figure 35). Although there is a slight variation over time for all scenarios, this is not captured in the figure mostly due to the scale at which it is drawn. Yield is lowest under the scenario where there is an increase in the cost of natural gas. This is expected given the lower irrigation level under this scenario, which was discussed above.

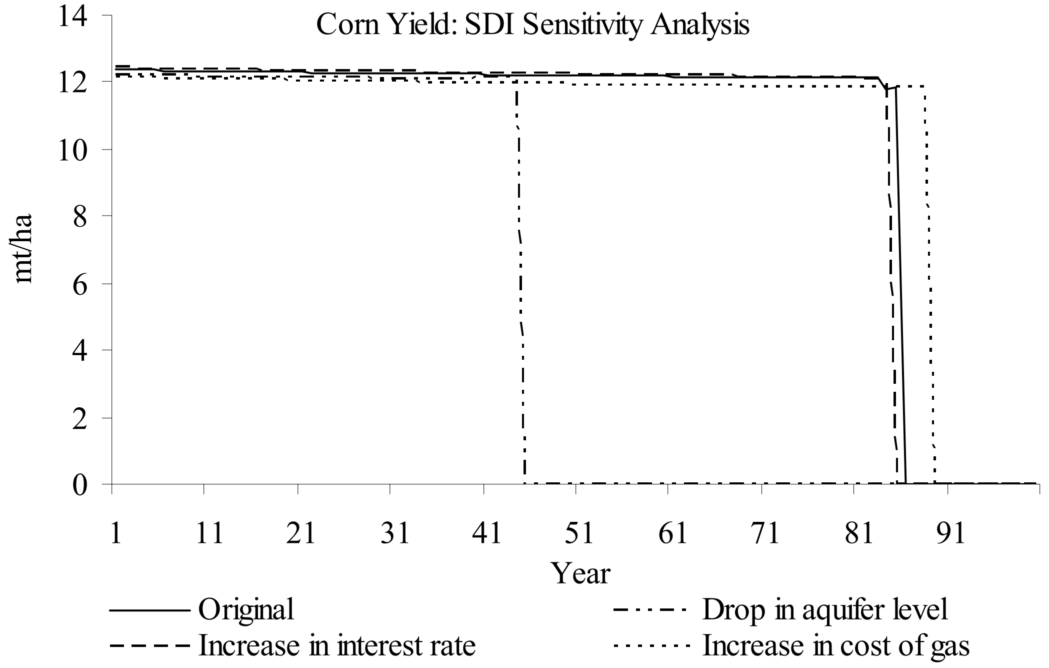


Figure 35. Sensitivity Analysis for Irrigated Corn Yield under SDI for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

The projected level of soil nitrogen seems to vary across all scenarios, but this variability has a range of less than 5 kg/ha at any point in time (Figure 36). The main reason for this variability is the fact that in the stochastic model, the states assigned for soil nitrogen were not continuous. Because of the nature of nitrogen, there is not much accumulation of nitrogen in the soil over time, thus the scale at which the figure is drawn also contributes to make these slight variations more visible. On the other hand, scaling has the inverse effect on the level of soil phosphorus (Figure 37).

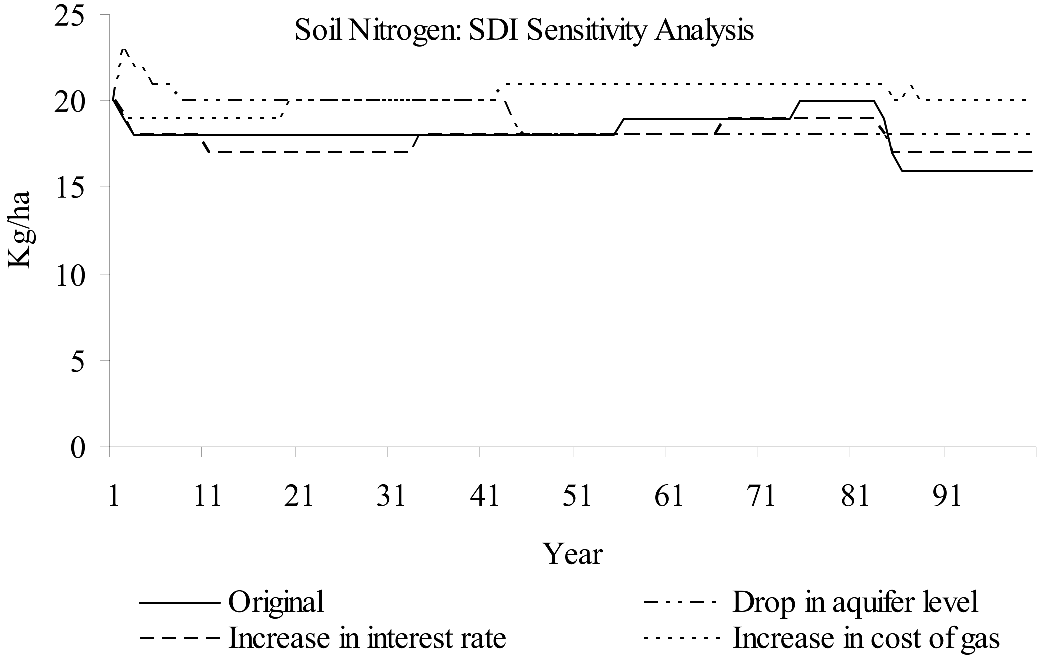


Figure 36. Sensitivity Analysis for Soil Nitrogen under SDI to Produce Irrigated Corn for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

Over long periods of effluent application, phosphorus tends to accumulate in the soil because it is a nutrient that is less essential for plant development compared to water and nitrogen and thus phosphorus removal through corn yield is not as great. It is also a fairly stable nutrient in the soil as it is not as mobile as nitrogen. For this reason phosphorus accumulation in the soil (Figure 37) was expected and the results of the analysis are consistent with previous empirical work (see Sharpley et al., 1991).

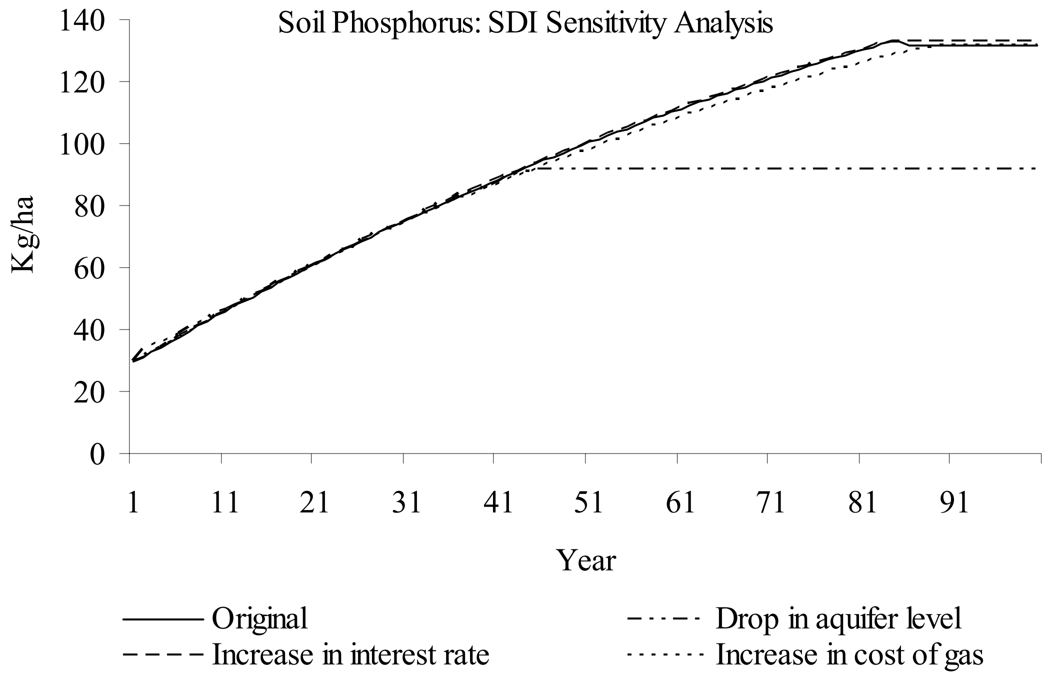


Figure 37. Sensitivity Analysis for Soil Phosphorus under SDI to Produce Irrigated Corn for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

Sensitivity Analysis for Center Pivot Sprinkler

The sensitivity analysis for the CPS exhibits is somewhat similar to that of the SDI with the exception of aquifer life and increased variability of key variables, both of which are greater with the CPS. The results for the center pivot sprinkler analysis show that the life of the aquifer is extended (Figure 38) compared to the results from the subsurface drip irrigation (Figure 32). With the center pivot, more water is available at the beginning of the production horizon because less area is under irrigation. There is not much difference in terms of what happens to remaining water in aquifer between the original scenario and the scenario in which the discount rate is increased from 5% to 10%.

Under the scenario where we cut the initial water supply in half, the economic exhaustion of the aquifer occurs around year 53, later than with the SDI, because less area is irrigated with CPS. When the cost of natural gas is increased from \$3.50 to \$5 per 1000 cubic feet, the economic exhaustion of the aquifer would occur around year 90 and more water would be left in the aquifer. The justification for this is similar to what was presented in the sensitivity analysis section for the stochastic SDI model, as an increase in the cost of natural gas requires that an additional unit of water extracted to have a higher marginal benefit. Because the marginal product (as well as benefit) of water declines as additional units are applied, this requires that less water be applied under this scenario Figure 39).

The level of irrigation applied is projected in Figure 39 and it is not as smooth as with the SDI because greater variability exists per irrigated hectare due to ammonia volatilization. None of the scenarios seem to have an effect on the level of variability. Similarly, the level of effluent applied also shows greater variability (Figure 40) than with the SDI for all scenarios considered, which is related to the higher variance associated with yield and ammonia volatilization under the CPS. As advanced earlier a possible explanation for this fact lies in the higher variance of ammonia volatilization with center pivot sprinkler irrigation.

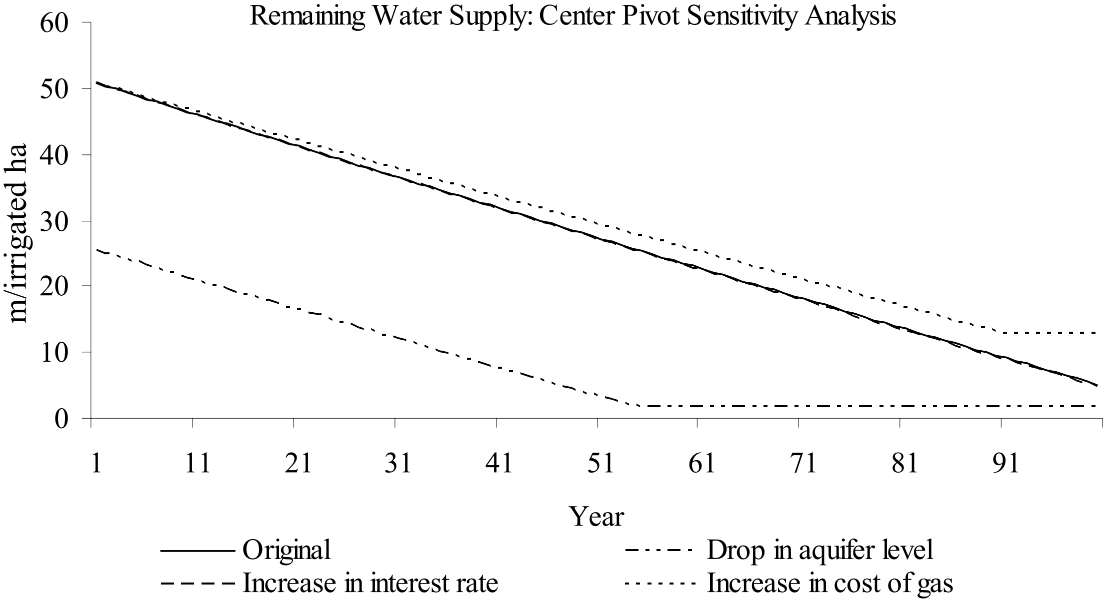


Figure 38. Sensitivity Analysis for Remaining Water Supply Using CPS to Produce Irrigated Corn for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

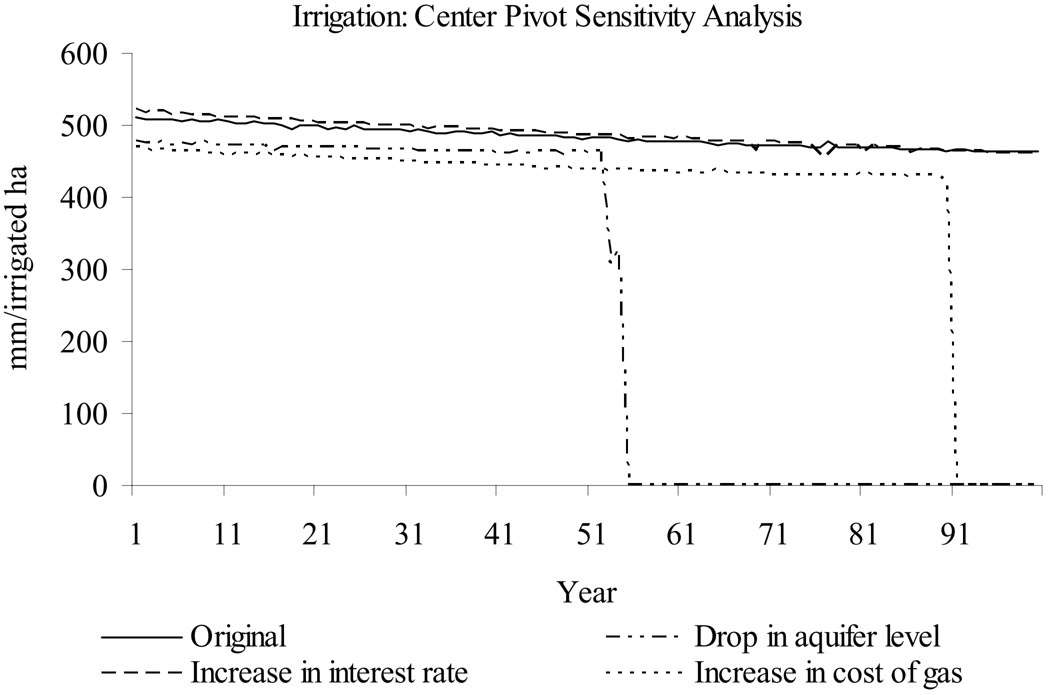


Figure 39. Sensitivity Analysis for Amount of Water Used in Irrigation under CPS to Produce Irrigated Corn for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

The projected irrigated corn yield using center pivot sprinkler irrigation is illustrated in Figure 41. When irrigation occurs, irrigated corn yield is slightly below 12 mt/ha under all scenarios, which is lower than with the SDI. Although barely noticeable in the figure because of the scaling effect, more variability occurs in yield with the CPS. The variability of soil nitrogen (Figure 42) is more noticeable because of the scale and compared to the SDI it is slightly more variable. However the level of soil nitrogen remains stable over time, as removal is very similar to application.

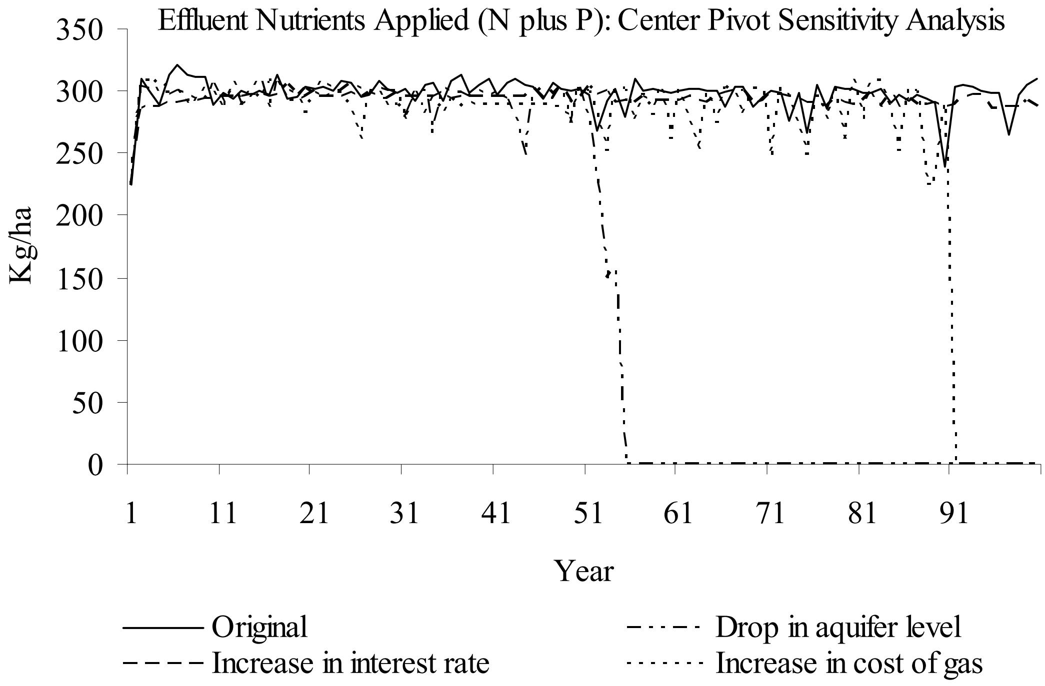


Figure 40. Sensitivity Analysis for Level of Effluent Nutrients Applied (Nitrogen plus Phosphorus) to Irrigated Corn under CPS for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

Once again, soil phosphorus accumulates over time (Figure 43), a result that was seen previously with the SDI (and was also present in the deterministic analysis). Soil phosphorus accumulation is lowest for the scenario where less water is available in the water table. The level of soil phosphorus accumulation predicted in the model seems low compared to previous field studies. After four years in which beef and swine manure were applied to a conventionally tilled crop production system located in the Oklahoma Panhandle Research and Extension Center, Goodwell, Oklahoma the soil test phosphorus was approximately 70, much higher than what this study would have predicted (Turner and Hattey, 2004, Personal Communication).

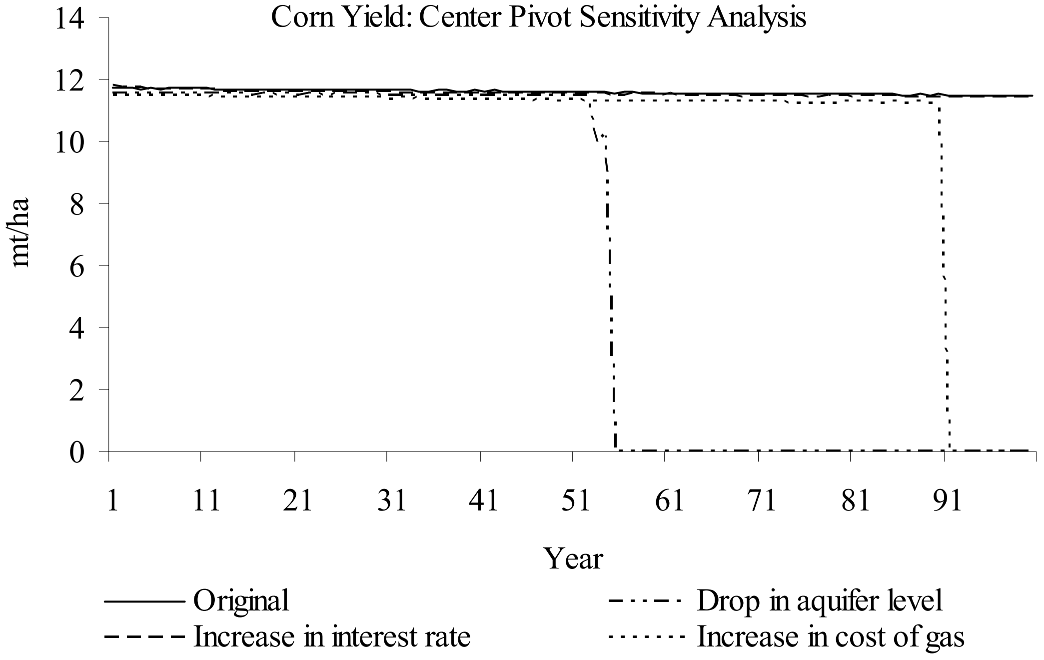


Figure 41. Sensitivity Analysis for Irrigated Corn Yield under CPS for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

Although the advantage of the SDI was not as high in the stochastic results as it was in the deterministic results, the SDI still was the most profitable irrigation system under all scenarios considered (Table 15). The shrinkage of the SDI monetary advantage has to with the fact that since a larger area is irrigated under this system, the economic exhaustion of the aquifer occurs earlier than with the CPS.

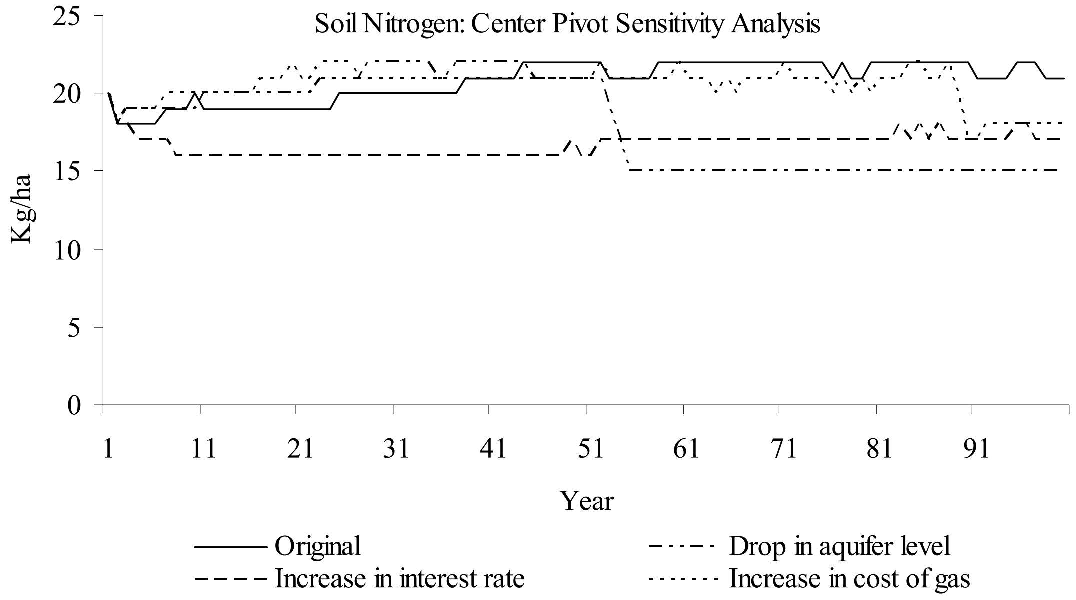


Figure 42. Sensitivity Analysis for Soil Nitrogen under CPS to Produce Irrigated Corn for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

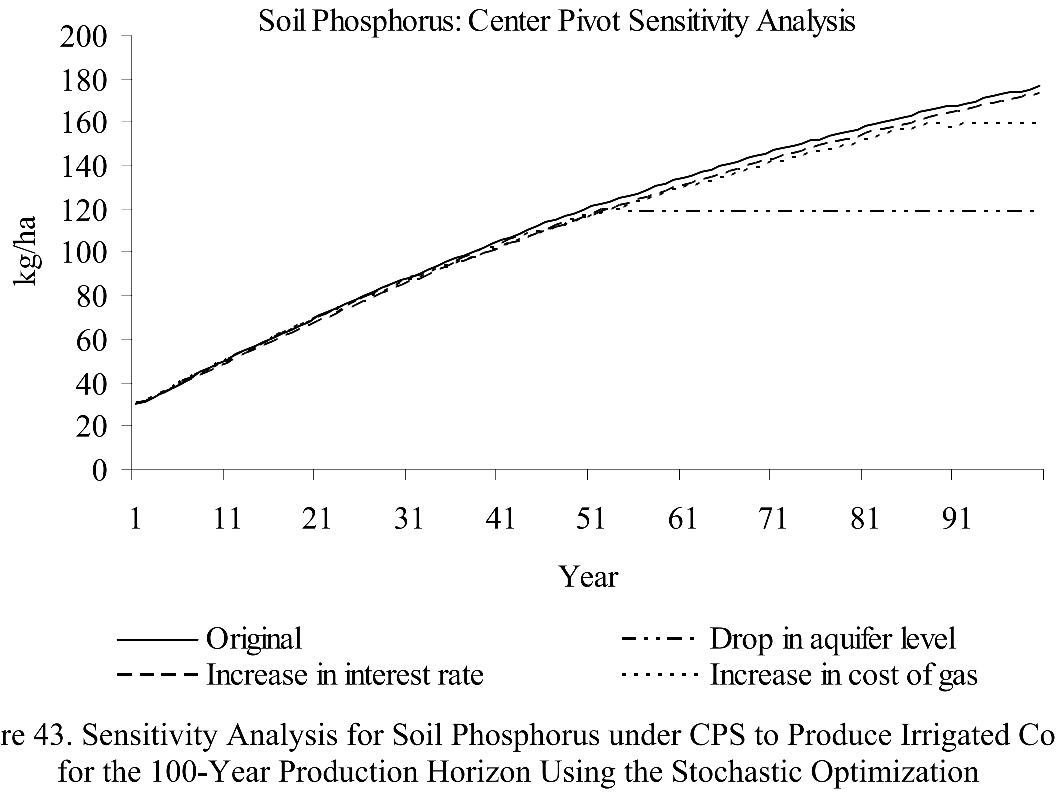


Figure 43. Sensitivity Analysis for Soil Phosphorus under CPS to Produce Irrigated Corn for the 100-Year Production Horizon Using the Stochastic Optimization Procedure

Effluent application requires irrigation, thus when irrigation is cut short, effluent application must also be cut short. The same thing happened in the scenario where the cost of natural gas is higher, although the reduction soil phosphorus was not as marked.

However, the difference in aquifer life is not significant enough to result in a disadvantage for the SDI, as can be seen from the results for the scenario where water supply in aquifer was cut in half. A rational risk averse or risk neutral producer choosing between the two irrigation systems and basing their decision in terms of expected net revenue and variance, will always choose the SDI, despite its higher implementation cost, assuming that their preferences are the same as the ones assumed in this analysis.

The SDI always has a NPV of the certainty equivalent higher than the CPS. The certainty equivalent is the amount of money an agent is willing to receive to not participate in a risky activity. For a risk averse agent, it is always lower than the expected net income as the agent is willing to forfeit part of the income to reduce their exposure to risk, this difference is the risk premium. For the scenario in which the initial aquifer level was cut in half, the risk premium was \$154 for the SDI and \$156 for the CPS for the production horizon. For the remaining scenarios the risk premium varied between \$324 and \$377. The risk premiums are therefore not very large considering the 100-year production horizon.

Table 15. Sensitivity Analysis for Stochastic Dynamic Optimization Model

		Irrigation System & Scenario							
		Subsurface Drip Irrigation				Center Pivot Sprinkler Irrigation			
Variables	Unit	Original	½ W_{Sup}	r=10%	$P_{nat.gas}=\$5$	Original	½ W_{Sup}	r=10%	$P_{nat.gas}=\$5$
Irrigation Level									
Irrigation Life	years	85	44	84	88	100	54	100	90
Annual average/irrigated area	mm/ha	482	466	488	439	484	462	487	444
Lifetime application to QS	M	2,568	1285	2,572	2,424	2,468	1,273	2,485	2,039
Effluent Applied									
Annual average/irrigated area	kg/ha	266	264	268	261	298	288	293	288
Lifetime application to QS	Mt	1,420	729	1,411	1,439	1,520	794	1,494	1,322
Soil Nitrogen									
Average over time and area	kg/ha	19	20	18	20	21	21	17	21
Soil Phosphorus									
Average over time and area	kg/ha	88	63	87	88	114	80	111	104
Corn Yield									
Annual average/irrigated area	mt/ha	12.2	12.1	12.3	12.0	11.6	11.5	11.5	11.3
Lifetime production of QS	mt	65,151	33,516	64,605	66,036	59,180	31,545	58,851	52,081
Net Present Value									
Lifetime Expected NR (farm)	$	512,026	446,367	264,581	437,812	474,448	424,778	240,321	413,933
Certainty Equivalent (farm)	$	511,702	445,990	264,427	437,474	474,122	424,406	240,165	413,598

Notes:

The four scenarios considered are i. original scenario; ii. reduction of initial water supply/aquifer level by 50 percent; iii. increase in real discount rate from 5 to 10 percent; and iv. increase in cost of natural gas from $3.50 to $5 per 1000 cubic feet.

Unless otherwise noted, averages over area refer to averages taken over irrigated area (62.73 hectares for SDI and 50.99 hectares for center pivot).

Averages over time refer to averages taken over the production horizon, assumed to be 100 years or over irrigated time life, whichever one is shortest.

Irrigated land is cultivated with corn, until aquifer becomes economically depleted; dry-land is cultivated with wheat.

Expected Net Revenue refers to revenues of irrigated (cultivated with corn) and non-irrigated land (cultivated with wheat).

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The intent of this study was to analyze the economic implications of alternative irrigation systems (subsurface drip water irrigation and center pivot sprinkler irrigation) in Texas County, Oklahoma, a region facing a finite water supply that is declining rapidly. Texas County is also a region where swine production has rapidly increased in the past 14 years and population concerns have risen because of the large amount of swine effluent produced. The basis for the comparison between the two systems was a representative farm, which was assumed to contain four quarter sections, one of which produced irrigated corn and the remaining sections produced dry-land wheat. The nutrient source for irrigated corn was swine effluent and it was assumed that the production horizon was 100 years. The objectives of the study were to evaluate both irrigation systems in terms of soil nutrient accumulation, irrigated corn yield, water use and aquifer life, and expected net revenues over the production horizon. It was expected that the SDI system would perform better than the CPS because it promotes water and nitrogen conservation, both of which are essential for the production of corn and are tools that farmers use to reduce yield risk. However, given the high implementation cost of an SDI compared to a CPS, it was questionable whether the increased savings in water, nutrient use and increased yield of using the SDI would be sufficient to outweigh the cost differential between the two systems. Two types of analysis were performed to compare both systems: a deterministic dynamic programming optimization and a stochastic dynamic programming optimization.

Discussion of Findings and Conclusions

After data were simulated in EPIC, econometric relationships were estimated for several equations: irrigated corn yield, soil nitrogen carryover, soil phosphorus carryover, and nitrogen percolation. A probability distribution for ammonia volatilization was also estimated building upon the theoretical work of Taylor (1984). The estimated relationships had parameters that were consistent which our initial expectations. For example, the parameter for nitrogen in effluent applied was positive indicating that soil nitrogen increased when effluent was applied. In the yield function, the dummy variable for irrigation system indicated that *ceteris paribus* corn yield was higher with the SDI than with the center pivot sprinkler.

A traditional budget approach comparing the annual net returns of the SDI with the CPS resulted in a small monetary advantage for the center pivot ($11,396 vs. $10,692 for the irrigated quarter section). The main reason for this result was the big implementation cost difference in favor of the center pivot. Assuming that each system has a lifetime of 15 years and its cost is amortized at a rate of 5%, the center pivot system has an annual cost of $4,621, less than half of the annual cost of the SDI, $10,294.

However, despite its short term disadvantage, the SDI system proved to be economically more profitable in the deterministic dynamic analysis and in the stochastic dynamic analysis when using a 100-year production horizon. The advantage of the SDI derives from several reasons: the system can cover a larger area, irrigated corn yield is slightly higher with the SDI given the same amount of inputs applied, and the SDI system offers less ammonia volatilization variability as well as less evaporation, thus it conserves inputs (water and nitrogen) per ha. The advantage of the SDI compared to the CPS for the quarter section using the deterministic analysis (this analysis is equivalent to assuming a risk-neutral producer) for the irrigated quarter section assuming a 100-year planning horizon was $95,381 (this amount is the difference between the NPV of the net returns of each system), less than $1,000 annually.

The results from the sensitivity analysis also indicated that the SDI was the best system in terms of net revenue over all the scenarios considered: a decline in the initial water supply, a higher discount rate, and an increase in the cost of natural gas which increases the cost of extracting water from the aquifer. The advantage of the SDI is lower for a risk averse producer (stochastic model) because economic exhaustion of the aquifer occurs earlier with the SDI than with the CPS (projected net present value of expected net revenue of farm over the 100-year production horizon was $512,026 for the SDI and $474,927 for the CPS). Monetary incentives to adopt the SDI were not included in the analysis, thus the advantage of the SDI can be greater if producers take advantage of incentives such as the ones offered via the Environmental Quality Incentives Program, EQIP.

In terms of aquifer conservation, increasing the cost of extracting water from the aquifer via an increase in the cost of natural gas, increases aquifer life and leaves more water in the aquifer after its economic depletion. Although the SDI is a system that is more expensive and is more management intensive than the center pivot sprinkler, it is a less riskier system in terms of nutrient management. For this reason, the optimal level of nutrient management is not as variable when SDI is used. The results indicate that the level of soil nitrogen is predicted to be stable over time with both systems, although more volatile for the CPS than for the SDI. The level of soil phosphorus is predicted to increase over time, although less accumulation should occur with the SDI because less effluent is applied and a higher corn yield leads to more nutrient removal. The model seems to underestimate phosphorus accumulation in the soil compared to actual field studies.

The use of alternative analysis procedures provides a greater insight to the nature of the problem. Sometimes a simplistic analysis like budgeting may provide misleading results. More sophisticated analysis, such as deterministic dynamic optimization or even stochastic dynamic optimization, capture several important aspects of the problem that can be overlooked in static analysis and can improve the decision making process.

Recommendations

Based on the previous analysis and assuming that it captures producer preferences correctly, subsurface drip irrigation is economically more competitive than center pivot irrigation for regions that have the same characteristics as Texas County, Oklahoma. Although the advantage of the SDI is not very big annually, it is always positive, thus this system should be taken into account for periods longer than 15 years, the lifetime of the irrigation systems assumed in this study. Producers are advised to seriously consider the SDI as an alternative to CPS when irrigating in the Oklahoma Panhandle. Even without the current monetary incentives given through the EQIP, the SDI is comparatively more advantageous than the CPS. Farmers as well as policy makers should also monitor phosphorus accumulation in soil when effluent is land applied, as the model projected that some accumulation should occur.

Concluding Remarks and Study Limitations

The conclusions of this study are valid given its assumptions. Although the conclusion that the SDI is economically more advantageous than the CPS was invariant to all the scenarios considered in the sensitivity analysis, there may be other scenarios where it does not hold. The difference in irrigation evaporation is included in the study, but future studies should consider making it a stochastic component of the model. The inclusion of urea as a choice variable in the model should be investigated. The present study relies on the use of expectations based on underlying probability distributions. Future studies should also consider stochastic dominance as an analysis tool for the comparison of risk between subsurface drip irrigation and center pivot sprinkler irrigation. Another interesting improvement could be a Game Theory approach with the introduction of another farm competing for the same water supply.

BIBLIOGRAPHY

Beattie, B.R., C.R. Taylor. 1993. *The Economics of Production.* Krieger Publishing Company, Malabar, Florida.

Bolker, J. 1998. *Writing Your Dissertation in Fifteen Minutes a Day*. Henry Holt and Company, New York.

Bostwick, D. 1962. "Yield Probabilities as a Markov Process." *Agricultural Economics Research,* 14: 49-58.

Branstetter, Z. 1997. "'Economic Boom' or Environmental Nightmare?" *Tulsa World*, May 5, 1997, Final Home ed. Sec News p. A13.

Camp, C.R. 1998. "Subsurface Drip Irrigation: A Review." *Transactions of the ASAE,* 41(5):1353-1367.

Camperato, J., B. Lippert, J. Chastain, and O. Plank. 1996. "Land Application of Animal Manure." *http://hubcap.clemson.edu/~blpprt/manure.html*. Last accessed November 12, 2004.

Cassman, K.G., A. Dobermann, and D.T. Walters. 2002. "Agroecosystems, Nitrogen-Use Efficiency, and Nitrogen Management." *Ambio* 3(2):132-139.

Chapelle, F.H. 1997. *The Hidden Sea: Ground Water, Springs, and Wells."* Geoscience Press, Tucson.

Crozier, C.R., L.D. King, and R.J. Volk. 1998. "Tracing Nitrogen Movement in Corn Production Systems in the North Carolina Piedmont: A Nitrogen-15 Study." *Agronomy Journal*, 90(2):171-177.

Cuykendall, C.H., and C.B. White. 1998. *Economics of Drip Irrigation for Apple Orchards in New York State*. Cornell University. Ithaca, New York.

Cuykendall, C.H., G.B. White, B.E. Schaffer, A.N. Lakso, and R.N. Dunst. 1999. *Economics of Drip Irrigation for Juice Grape Vineyards in New York State*. Cornell University. Ithaca, New York.

Economic Research Service/United States Department of Agriculture. 1996. "1996 FAIR Act Frames Farm Policy for 7 Years." *Agricultural Outlook Supplement*, April 1996.

Gray, A.W., M.D. Boehlje, B.A. Gloy, and S.P. Slinsky. 2004. "How U.S. Farm Programs and Crop Insurance Affect Returns to Farm Land." *Review of Agricultural Economics,* 26(2):238-253.

Greene, W.H. 2000. *Econometric Analysis-Fourth Edition."* Prentice Hall, Upper Saddler River.

Harris, T.R., H.P. Mapp, and J.F. Stone. 1983. *Irrigation Scheduling in the Oklahoma Panhandle: An Application of Stochastic Efficiency and Optimal Control Analysis—Oklahoma Agricultural Experiment Station Technical Bulletin no. 160.* Oklahoma State University: Stillwater, Oklahoma.

Hill, J.S. 2001. Personal Communication. Lecturer at Baylor University.

Hillier, F.S., and G.J. Lieberman. 1980. *Introduction to Operations Research, 3rd ed.* Holden-Day, San Francisco, California.

Hinton, M. 1998. "Hog Bill Called Nation's Strictest Keating Hails Success; Swine Farmers Criticize" *The Daily Oklahoman* June 11, 1998, City ed. Sec News p. 1.

Howell, T.A., A.D. Schneider, and S. R. Evett. 1998. "Subsurface and Surface Microirrigation of Corn—Southern High Plains." *Transactions of the ASAE*, 40(3):635-641.

James, L.G. 1988. *Principles of Farm Irrigation System Design*. John Wiley & Sons, New York.

Johnson, A.F., D.M. Vietor, F. M. Rouquette, Jr., V.A. Haby, and M.L. Wolfe. 1995. "Estimating the Probabilities of Nitrogen and Phosphorus Loss from Animal Waste Application." In *Animal Waste and the Land-Water Interface,* ed. K. Steele. Lewis Publishers, Boca Raton.

Just, R.E. and Q. Weninger. 1990. "Are Crop Yields Normally Distributed?" *American Journal of Agricultural Economics,* 81:287-304.

Just, R.E. and R.D. Pope. 2003. "Agricultural Risk Analysis: Adequacy of Models, Data, and Issues" *American Journal of Agricultural Economics,* 85:1249-1256.

Kalvelagen, E. 2002. "Benders Decomposition with GAMS," *http://www.gams.com/~erwin/benders/benders.pdf,* December 2002.

Kalvelagen, E. 2003. “Some MINLP Solution Algorithms,” *http://www.gams.com/~erwin/minlp/minlp.pdf,* September 2003.

Kennedy, J.O.S. 1986. *Dynamic Programming: Applications to Agriculture and Natural Resources.* Elsevier Applied Science Publishers, New York.

Kemeny, J.G. and J.L. Snell. 1976. *Finite Markov Chains.* Springer-Verlag, New York.

Kletke, D. and D.G. Doye. 1998. “Oklahoma Farm and Ranch Custom Rates, 1999-2000” *Current Report* CR-205, updated March 3, 2004. Oklahoma Cooperative Extension Service, Oklahoma State University.

Kochenower, R. and C.A. Strasia. 2002. “Oklahoma Panhandle Corn Performance Trial, 2002.” *Production Technology Crops*, 14(26), November 2002. http://oaes.pss.okstate.edu/goodwell/Publications/corn%202002.pdf. Last accessed November 1, 2004.

________. 2003. “Oklahoma Corn Performance Trials, 2003.” *Production Technology Crops*, 15(16), November 2003. http://oaes.pss.okstate.edu/goodwell/Publications/corn%20pt%202003.pdf. Last accessed November 1, 2004.

Kromm, D.E. and S.E. White. 1992a. *Groundwater Exploitation in the High Plains*. University Press of Kansas, Lawrence.

________. 1992b. “Groundwater Problems.” In *Groundwater Exploitation in the High Plains*, ed. Kromm, D. E. and S. E. White. University Press of Kansas, Lawrence.

Lamm, F.R. 2003. “KSU Research for Corn Production Using SDI: 14 Years of Progress.” Agricultural Experiment Station and Cooperative Extension service, Kansas State University. *http://www.oznet.ksu.edu/sdi/reports/2003/SDI14YrP.pdf.* Last accessed Sept. 12, 2003.

Lamm, F.R., D.H. Rogers, M. Alam, and G.A. Clark. 2003. *Design Considerations for Subsurface Drip Irrigation (SDI) Systems*. Kansas State University, July 2003. *http://www.oznet.ksu.edu/library/ageng2/mf2578.pdf.* Last accessed Nov. 12, 2003.

Lamm, F.R., T.P. Trooien, H.L. Manges, and H.D. Sunderman. 2001. “Nitrogen Fertilization for Subsurface Drip-Irrigated Corn.” *Transactions of the ASAE*, 44(3):533-442.

Lamm, F.R., T.P. Trooien, L.R. Stone, M. Alam, D.H. Rogers, G.A. Clark, and A.J. Schlegel. 2000. “Using Livestock Wastewater with SDI—A Status Report After Four Seasons.” In *Proceedings of the 2002 Central Plains Irrigation Short*

Course, Lamar, CO., Feb. 5-6, 2002. Available from CPIA, 760 N. Thompson, Colby, KA. pp 8-15.

Lewis, J. 1990. "The Ogallala Aquifer: An Underground Sea." *EPA Journal* 16(6):42-44.

Martin, H. 2003. "Kansas Farmers Look Forward to First SDI Corn Crop" *High Plains Journal,* September 8, 2003.

Nijland, G.O., J. Schouls. 1997. *The Relationship between Crop Yield, Nutrient Uptake, Nutrient Surplus and Nutrient Application.* Backhuys Publishers, Leiden, The Netherlands.

O'Brien, D.M., T.J. Dumler, and D.H. Rogers. 2001. "Irrigation Capital Requirements and Energy Costs." Agricultural Experiment Station and Cooperative Extension Service, Kansas State University. *http://www.oznet.ksu.edu/library/agec2/mf836.pdf.* Last accessed Dec. 2, 2003.

O'Brien, D.M., D.H. Rogers, F.R. Lamm, and G. Clark. 1997. "Economic Comparison of SDI and Center Pivots for Various Field Sizes." Agricultural Experiment Station and Cooperative Extension Service, Kansas State University. *http://www.oznet.ksu.edu/library/ageng2/mf2242.pdf.* Last accessed Sept. 12, 2003.
________. 1998. "An Economic Comparison of Subsurface Drip and Center Pivot Sprinkler Irrigation Systems." *Applied Engineering in Agriculture*, 14(4):391-398.

Oron, G., and Y. DeMalach. 1987. "Reuse of Domestic Wastewater for Irrigation in Arid Zones: A Case Study," *Water Resources Bulletin,* 23(5):777-783.

Peterson, J.M., T.L. Marsh, and J.R. Williams. 2003. "Conserving the Ogallala Aquifer: Efficiency, Equity, and Moral Motives." *Choices*, February 2003(1): 15-18. http://www.choicesmagazine.org/archives/2003/q1/2003-1-04.htm

Phene, C.J., and R.C. Phene. 1987. "Drip Irrigation Systems and Management," *Food and Fertilizer Technology Center Extension Bulletin* 244 January 1987.

Raun, W.R., and G.V. Johnson. 2002. "Improving Nitrogen Use Efficiency for Cereal Production." *Agronomy Journal,* 91(3):357-363.

Reinke Manufacturing Company, Inc. 2003. *Irrigation Catalog*. Deshler, Nebraska. http://www.reinke.com.

Rogers, D.H., F.R. Lamm, and M. Alam. 2003. *Subsurface Drip Irrigation (SDI Components: Minimum Requirements*. Kansas State University, July 2003. *http://www.oznet.ksu.edu/library/ageng2/mf2576.pdf.* Last accessed Nov. 12, 2003.

Rutegård,G., L. Lönnstedt, and M. Kallio. 2003. "Acquisition of a Forest State: A Stochastic Optimization Approach for Financing and Management." *Forest Science,* 49(5):706-718.

Scherer, T.F., W. Kranz, D. Pfost, H. Werner, J.A. Wright, and C.D. Yonts. 1999. *Sprinkler Irrigation Systems*. Mid West Plan Service, Iowa State University, Ames, Iowa.

Schumacher Irrigation, Inc. 1998. *Irrigation Catalog*. Platte Center, Nebraska. http://www.schumacherirrigation.com/

Sharpley, A.N. B.J. Carter, B.J. Wagner, S.J. Smith, E.L. Cole, and G.A. Sample. 1991. "Impact of Long-Term Swine and Poultry Manure Application on Soil and Water Resources in Eastern Oklahoma." Agricultural Experimental Station, Oklahoma State University, Technical Bulletin T-169.

Sorensen, R.B., F.S. Wright, and C.L. Butts. 2001. "Subsurface Drip Irrigation System Designed for Research in Row Crop Rotations," *Applied Engineering in Agriculture,* 17(2):171-176.

Stichler, C. and M. McFarland. 2001. *Crop Nutrient Needs in South and Southwest Texas*. Texas Agricultural Extension Service. http://texaserc.tamu.edu.

Stoecker, A.L., and A.B. Onken. 1989. "Optimal Fertilizer Nitrogen and Residual Nitrate-Nitrogen Levels for Irrigated Corn and Effects of Nitrogen Limitation: An Economic Analysis," *Journal of Production Agriculture,* 2(4):309-317.

Stoecker, A.L., A. Seidman, and G.S. Lloyd. 1985. "A Linear Dynamic Approach to Irrigation System Management with Depleting Groundwater," *Management Science,* 31(4):422-434.

Stryker, J. 2003. *Jess Stryker's Irrigation System Design Guidelines*. http://www.irrigationtutorial.com/. Last accessed Nov. 6, 2003.

Taylor, C.R. 1984. "A Flexible Method for Empirically Estimating Probability Functions." *Western Journal of Agricultural Economics,* 9(1):66-76.

________. 1990. "Two Practical Procedures for Estimating Multivariate Nonnormal Probability Density Functions." *American Journal of Agricultural Economics,* 72(1):210-217.

Templer, O.W. 1992. "The Legal Context for Groundwater Use." In *Groundwater Exploitation in the High Plains*, ed. Kromm, D. E. and S. E. White. University Press of Kansas, Lawrence.

Turabian, K.L. 1996. *A Manual for Writer of Term Papers, Theses, and Dissertation*, 6th ed., The University Chicago Press, Chicago.

Turner, J.C. and J.A. Hattey. 2004. Personal Communication. Oklahoma State University.

U-Kosaramig, L. 2001. "Field Evaluation of an Automated subsurface Drip Irrigation System Utilizing Dairy Wastewater for the Irrigation of Alfalfa," Unpublished M.S. Thesis, California State University, Fresno, May 2001.

United States Department of Agriculture, Soil Conservation Service. 1961. *Soil Survey of Texas County, Oklahoma.*

United States Department of Agriculture, National Agricultural Statistics Service.1999. *1997 Census of Agriculture.*

United States Department of Agriculture, National Agricultural Statistics Service. 2004. *2002 Census of Agriculture.*

Valentine, H.T. and G.M. Furnival. 1989. "Projections with Ingrowth Markov Chains," *Forest Science,* 35(1):245-250.

Warren, J.G. , J.A. Hattey, J.C. Turner, and J.W. Parton. 2000. "Ammonia Volatilization from Surface Applied Swine Effluent as Affected by Crop Cover," *Agronomy Abstracts,* p. 398. American Society of Agronomy, Madison, WI.

Wikimedia Foundation Inc. 2004. "Markov Chain," *Wikipedia the Free Encyclopedia. http://en.wikipedia.org/wiki/Markov_chain,* last accessed April 6, 2004.

Wikimedia Foundation Inc. 2004. "Markov Property," *Wikipedia the Free Encyclopedia. http://en.wikipedia.org/wiki/Markov_property,* last accessed April 6, 2004.

Wu, J., D.L. Nofziger, J.G. Warren, and J.A. Hattey. 2003a. "Modeling Ammonia Volatilization from Surface-Applied Swine Effluent," *Soil Science Society of America Journal*, 67:1-11.

Wu, J., D.L. Nofziger, J.G. Warren, and J.A. Hattey. 2003b. "Estimating Ammonia Volatilization from Swine-Effluent Droplets in Sprinkle Irrigation," *Soil Science Society of America Journal*, 67:1352-1360.

Yadav, S.N. 1997. "Dynamic Optimization of Nitrogen Use When Groundwater Contamination Is Internalized at the Standard in the Long Run." *American Journal of Agricultural Economics,* 79(3):931-945.

Zhang, H. and D.W. Hamilton. 2002. "Using Lagoon Effluent as Fertilizer," *Oklahoma Cooperative Extension Fact Sheets,* Oklahoma State University, Stillwater, *http://www.osuextra.com*.

Zhang, H. 2002. “Oklahoma Agricultural Soil Test Summary 1994-1999,” *Oklahoma Cooperative Extension Fact Sheets,* Oklahoma State University, Stillwater, *http://www.osuextra.com*.

________. 2003. “Fertilizer Nutrients in Animal Manure,” *Oklahoma Cooperative Extension Fact Sheets,* Oklahoma State University, Stillwater, *http://www.osuextra.com*.

Zupancic, K.S., 1999. “Determination of Ammonia Flux from Swine Effluent Applied to Calcareous Soils,” Unpublished M.S. Thesis, Oklahoma State University, Stillwater, May 1999.

APPENDIXES

APPENDIX A—SUBSURFACE DRIP IRRIGATION DESIGN

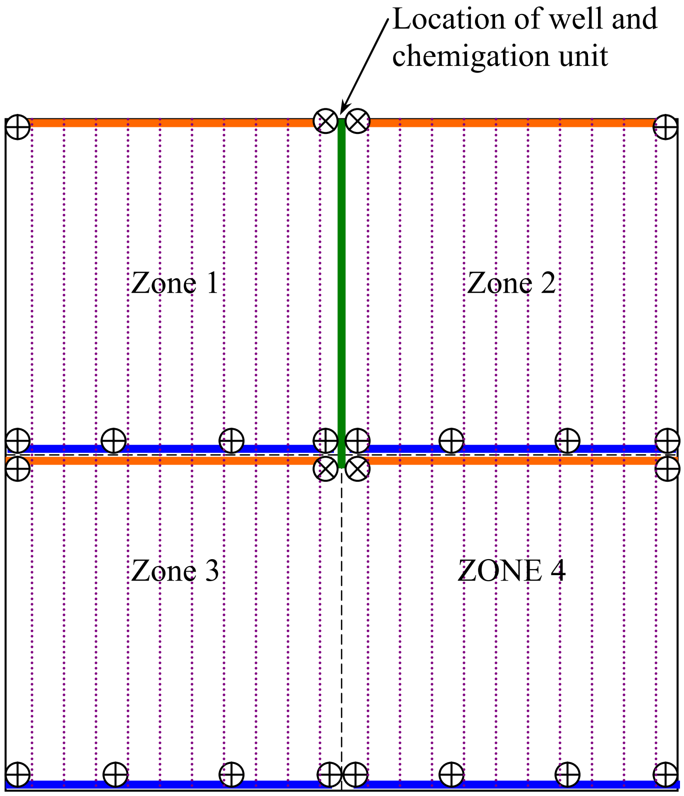


Figure 44. Schematic for Subsurface Drip Irrigation Design

Legend:

🟧	Submain line: 8-inch PVC pipe, 5,280 ft.
🟩	Main line: 8-inch PVC pipe, 1320 ft.
🟦	Flush line: 6-inch pipe, 5,280 ft.
⋯	Drip line: 7/8-inch polyethylene drip tube, 1,350,360 ft; lateral spacing 5 ft, corn row spacing 2.5 ft.
⊗	Zone valves
⊕	Flush valves

Notes:

1. Above drawing is not to scale.
2. Area: 160 acres; irrigated area: 155 acres.

APPENDIX B—SUBSURFACE DRIP IRRIGATION SYSTEM BUDGET

Table16. Subsurface Drip Irrigation System Cost for Quarter Section (64.75 ha)

SDI construction	Unit	$/Unit	Quantity	Total
Controller unit	Unit	$4,000.00	1	$4,000.00
8" supply line (mainline)	Feet	$1.72	1320	$2,270.40
8" manifold line	Feet	$1.72	5280	$9,081.60
6" flush line pipe	Feet	$1.10	5280	$5,808.00
7/8" barb adapter w/ neoprene grommets	Unit	$1.00	2112	$2,112.00
7/8" diameter drip tape, emitters: 24"	Feet	$0.05	1,350,360	$60,766.20
7/8" polyethylene supply tubing	Feet	$0.05	2112	$105.60
7" stainless steel wire ties	Unit	$0.10	2112	$211.20
2" pvc riser	Feet	$0.31	40	$12.40
Air vent	Unit	$30.83	20	$616.60
Ball valve	Unit	$13.50	20	$270.00
T for pvc riser	Unit	$2.60	20	$52.00
6" valve	Unit	$2,300.00	1	$2,300.00
Media sand filter 48" diameter w/ 4" outlet up to 400 gallon capacity	Unit	$3,957.00	2	$7,914.00
Trencher rental	Hour	$375.00	2	$750.00
Labor for trenching	Hour	$8.25	15.5	$127.88
Labor to install pipes	Foot	$0.10	11880	$1,188.00
Other labor	Hour	$8.25	984.5	$8,122.13
100 hp tractor w/ driver	Hour	$23.50	28.5	$669.75
2 laborers to install tubing	Hour	$8.25	57	$470.25
Total SDI Cost	$/QS			$106,848.01
Total SDI Cost/irrigated ha	$/ha			$1,703.30

Notes:

1. Irrigated area: approximately 62.73 ha.

Sources: Dr. Michael A. Kizer (Oklahoma State University), Knutson Irrigation (Yukon, OK), Schumacher Irrigation, Inc. (Platte Center, NE), Ditch Witch Rental (Stillwater, OK), Kletke, D. and Doye, D.G.

APPENDIX C—CENTER PIVOT IRRIGATION SYSTEM BUDGET

Table17. Center Pivot Irrigation System Cost for Quarter Section (64.75 ha)

Center Pivot System	Unit	$/Unit	Quantity	Total
Standard 7-tower pivot system base price (1320 ft.)	unit			$28,000.00
Drops on 80" spacing				$2,100.00
Low drift nozzles				$2,400.00
38" x 11.2 tires				$3,000.00
8" underground water pipe	feet	1320	$2.62	$3,459.00
Electrical wiring	feet	1320	$2.00	$2,640.00
Connectors				$1,500.00
12 KVA generator	unit			$2,375.00
TOTAL (2001 cost)	$			$45,474.00
Cost per irrigated acre (2001 cost)	$/acre			$360.90
Cost per irrigated hectare (2003 updated cost, assuming 3% annual cost increase)	$/ha			$946.76

Notes:

1. Area: 64.75 ha; irrigated area: 51.01 ha.
2. System lateral: 1,320 feet.

Source: O'Brien, Dumler, and Rogers (2001)

APPENDIX D—AMMONIA VOLATILIZATION PDF PROOF

The function described in Chapter III is a probability density function if and only if the following two conditions are met:

1. $f\left(V \middle| N,U\right) \geq 0, \forall V \in \mathbb{R}_0^+$
2. $\int_0^\infty f\left(V \middle| N,U\right) \mathrm{d}V = 1$

where $f\left(V \middle| N,U\right) = 0.5\left(\rho_1 - \rho_2 V^{-2}\right)\cosh^{-2}\left(\rho_0 + \rho_1 V + \rho_2 V^{-1} + \rho_3 N + \rho_4 U\right)$, $\rho_1 > 0$, and $\rho_2 < 0$. Before proving both conditions, recall the definition of hyperbolic cosine,

$$\cosh\left(x\right) = \frac{1}{2}\left(\exp(x) + (\exp(-x)\right).$$

Proof

The first condition is clearly true $\forall V \in \mathbb{R}^+$. For $V = 0$, the function is indeterminate of type $\infty 0$, thus its limit must be evaluated as $V \to 0^+$. Define a constant, *c*, to denote all the terms that are not a function of ammonia volatilization, i.e.,

$$c = \rho_0 + \rho_3 N + \rho_4 U,$$

then

$$\begin{aligned}
\lim_{V \to 0^+} f\left(V \middle| N,U\right) &= \lim_{V \to 0^+}\left[0.5\left(\rho_1 - \rho_2 V^{-2}\right)\cosh^{-2}\left(\rho_1 V + \rho_2 V^{-1} + c\right)\right] \\
&= \lim_{V \to 0^+}\left[0.5\rho_1 \cosh^{-2}\left(\rho_1 V + \rho_2 V^{-1} + c\right) - 0.5\rho_2 V^{-2}\cosh^{-2}\left(\rho_1 V + \rho_2 V^{-1} + c\right)\right] \\
&= \lim_{V \to 0^+}\left[0.5\rho_1 \cosh^{-2}\left(\rho_2 V^{-1} + c\right) - 0.5\rho_2 V^{-2}\cosh^{-2}\left(\rho_2 V^{-1} + c\right)\right]
\end{aligned}$$

$$= \lim_{V \to 0^+} \left[\frac{0.5\rho_1}{\left\{ \frac{1}{2} \left(\exp\left(\rho_2 V^{-1} + c \right) + \exp\left(-\rho_2 V^{-1} - c \right) \right) \right\}^2} \right.$$

$$\left. - \frac{0.5\rho_2}{\left\{ \frac{1}{2} V \left(\exp\left(\rho_2 V^{-1} + c \right) + \exp\left(-\rho_2 V^{-1} - c \right) \right) \right\}^2} \right]$$

$$= \lim_{V \to 0^+} \left[\frac{2\rho_1}{\left(1 + \exp\left(-\rho_2 V^{-1} - c \right) \right)^2} - \frac{2\rho_2}{V^2 \left(1 + \exp\left(-\rho_2 V^{-1} - c \right) \right)^2} \right]$$

$$= \lim_{V \to 0^+} \left[0 - \frac{2\rho_2}{0 + V^2 \left(\exp\left(-\rho_2 V^{-1} - c \right) \right)^2} \right]$$

$$= \lim_{V \to 0^+} \left[- \frac{2\rho_2}{V^2 \left(\exp(-c) \right)^2 \left(\exp\left(-\rho_2 V^{-1} \right) \right)^2} \right]$$

$$= \lim_{V \to 0^+} \left[- \frac{2}{\rho_2 \left(\exp(-c) \right)^2} \frac{1}{\left(\frac{\exp\left(-\rho_2 V^{-1} \right)}{-\rho_2 V^{-1}} \right)^2} \right]$$

$$= \lim_{V \to 0^+} \left[- \frac{2}{\rho_2 \left(\exp(-c) \right)^2} \frac{1}{\infty} \right]$$

$$= 0$$

Thus, $f\left(V \middle| N, U \right) \geq 0, \forall V \in \mathbb{R}_0^+$.

The second condition is proven as follows:

$$\int_0^\infty f\left(V \middle| N,U\right)\mathrm{d}V = \int_0^\infty 0.5\left(\rho_1 - \rho_2 V^{-2}\right)\cosh^{-2}\left(\rho_0 + \rho_1 V + \rho_2 V^{-1} + \rho_3 N + \rho_4 U\right)\mathrm{d}V$$

$$= 0.5\left[\tanh\left(\rho_0 + \rho_1 V + \rho_2 V^{-1} + \rho_3 N + \rho_4 U\right)\right]_0^\infty$$

$$= 0.5\left[1-\left(-1\right)\right]$$

$$= 1$$

Q.E.D.

Since the function satisfies both conditions, it is a PDF.

APPENDIX E—EXPERIMENTAL DESIGN USED TO SIMULATE YIELD DATA IN EPIC

The nutrient experimental design used to generate corn yield data in EPIC consisted of 10 different nutrient treatments set up as follows:

Table18. Nutrient Experimental Design Used to Simulate Yield Data in EPIC

Treat-	Effluent	N in Effluent			Total N	Other N	Total N	Total P	N/P
ment	Units	NO3	NH3	NO	Effluent	Urea	Applied	Effluent	Ratio
1	357.143	25	225	28.57	278.57	0.0	278.57	82.14	3.4
2	285.714	20	180	22.86	222.86	0.0	222.86	65.71	3.4
3	214.286	15	135	17.14	167.14	111.4	278.57	49.29	5.7
4	214.286	15	135	17.14	167.14	0.0	167.14	49.29	3.4
5	142.857	10	90	11.43	111.43	167.1	278.57	32.86	8.5
6	142.857	10	90	11.43	111.43	83.6	195.00	32.86	5.9
7	142.857	10	90	11.43	111.43	0.0	111.43	32.86	3.4
8	71.4286	5	45	5.71	55.71	222.9	278.57	16.43	17.0
9	71.4286	5	45	5.71	55.71	111.4	167.14	16.43	10.2
10	71.4286	5	45	5.71	55.71	0.0	55.71	16.43	3.4

Note: All variables in kg/ha except for N/P ratio, which is unitless.

The six irrigation levels considered were 113, 198, 283, 367, 452, and 565 millimeters per hectare. Three different weather patterns were generated for the simulation. Yield was simulated for 25 consecutive years but observations corresponding to the first four years were deleted. The number of observations used in the estimation was 7,560, i.e., 3780 for each system.

APPENDIX F—VALIDATION OF EPIC DATA

Current literature offers a few studies that have estimated corn yields in regions with climate similar to that of Texas County. Although the objective of these studies differs from the current study, their reported yields will serve as a validation reference for the data generated in EPIC. Table 19 reports the average irrigated corn yields as reported in some of these studies.

Table19. Irrigated Corn Yields as Reported by Previous Studies for Regions Similar to Texas County, Oklahoma

Study	Location	Irrigation Type/mm	N Applied (kg/ha)	Low Yield (tons/ha)	High Yield (tons/ha)
Howell, Schneider, & Evett (1998)	Bushland, Texas	DL/--		Mean 0.84	
		TOP/657	170	Mean 12.77	
		TOP/250	60	Mean 7.04	
		SUB/657	170	Mean 12.38	
		SUB/250	60	Mean 6.46	
O'Brien, Rogers, Lamm, Clark (1998)	Western Kansas	SDI/406	NA	Mean 11.93	
		CPS/457	NA	Mean 11.93	
Lamm, Trooien, Manges, Sunderman (2001)	Colby, Kansas	SDI/788	20	4.7	12.2
		SDI/788	143	11	13.4
		SDI/788	266	14.7	15.9
		SDI/578	11	4.4	9.2
		SDI/578	134	9.7	12.7
		SDI/578	257	13.6	14.4
Kochenower, Strasia (2002)	Goodwell, OK	CPS/406.4	179.34	7.78	11.17
	Guymon, OK	CPS/457.2	224.17	9.78	15.96
Kochenower, Strasia (2003)	Goodwell, OK	CPS/406.4	224.17	11.69	13.75
	Guymon, OK	CPS/406.4	224.17	9.58	12.29

Note: DL is dry land, TOP is surface micro-irrigation, SUB is subsurface micro-irrigation, SDI is subsurface drip irrigation, and CPS is center pivot sprinkler; NA refers to values that were not specified in the study.

Only the study by O'Brien, Rogers, Lamm, and Clark (1998) offers a comparison between the two irrigation systems, but unfortunately the average yield reported is a mere estimate. In their study, which presents a budget comparison of center pivot irrigation and subsurface drip irrigation, the mean corn yield obtained with each irrigation system is the same (11.93 tons/ha); what differs is the amount of water used with each system to obtain that yield. Thus their main assumption is that SDI used less water to obtain the same yield as center pivot sprinkler irrigation.

Actual yields are reported by Kochenower and Strasia (2002 and 2003). The yields reported for Goodwell correspond to the experimental station (Oklahoma Panhandle Research and Extension Center) yields, while the yields reported for Guymon are from Joe Webb farm. In both cases, the irrigation system used is center pivot sprinkler. The average yield for 2002 is 9.5 tons/ha in Goodwell and 12.87 tons/ha in Guymon. In 2003, irrigated corn yield in Goodwell was 12.72 and in Guymon it was 10.935. These numbers are within the values generated in EPIC for the CPS irrigation system, which are reported in tables 21 and 23: yield values generated by EPIC are between 3.3 and 15.2 tons/ha; average yield generated is between 6.32 and 10.83 by irrigation level (Table 23) and between 5.02 and 9.74 by nutrient treatment level (Table 21). For the SDI, the values generated by EPIC are between 3.5 and 15.2 tons/ha; while average yield generated is between 6.72 and 11.49 by irrigation level (Table 22) and between 5.68 and 10.11 by nutrient treatment level (Table 20). These EPIC averages are consistent with the work conducted at Kansas State University (O'Brien, Rogers, Lamm, and Clark, 1998; Lamm, Trooien, Manges, Sunderman, 2001). It may seem odd that there is not much variability in the EPIC yields, however this is not that strange if one considers that the weather patterns were controlled and each treatment was replicated for three weather patterns. With real world data, the weather pattern cannot be accounted for to the full extent of its effect.

Table20. Mean Irrigated Corn Yields by Nutrient Treatment for SDI as Simulated by EPIC

Treat-ment	Effluent Units (kg/ha)	Total N Applied (kg/ha)	Total P Effluent (kg/ha)	Mean Yield (tons/ha)	Standard Deviation (tons/ha)	Minimum Yield (tons/ha)	Maximum Yield (tons/ha)
1	357.143	278.57	82.14	10.11	2.54	3.60	15.20
2	285.714	222.86	65.71	10.11	2.54	3.60	15.20
3	214.286	278.57	49.29	10.11	2.54	3.60	15.20
4	214.286	167.14	49.29	9.84	2.28	3.60	14.00
5	142.857	278.57	32.86	10.11	2.54	3.60	15.20
6	142.857	195.00	32.86	10.09	2.52	3.60	15.00
7	142.857	111.43	32.86	8.35	1.42	3.60	12.30
8	71.4286	278.57	16.43	10.11	2.54	3.60	15.20
9	71.4286	167.14	16.43	9.91	2.34	3.60	14.20
10	71.4286	55.71	16.43	5.68	0.89	3.50	8.50

Table21. Mean Irrigated Corn Yields by Nutrient Treatment for Center Pivot Sprinkler Irrigation as Simulated by EPIC

Treat-ment	Effluent Units (kg/ha)	Total N Applied (kg/ha)	Total P Effluent (kg/ha)	Mean Yield (tons/ha)	Standard Deviation (tons/ha)	Minimum Yield (tons/ha)	Maximum Yield (tons/ha)
1	357.143	278.57	82.14	9.74	2.51	3.50	15.20
2	285.714	222.86	65.71	9.69	2.45	3.50	14.80
3	214.286	278.57	49.29	9.74	2.51	3.50	15.20
4	214.286	167.14	49.29	9.03	1.91	3.50	13.40
5	142.857	278.57	32.86	9.74	2.51	3.50	15.20
6	142.857	195.00	32.86	9.59	2.35	3.50	14.50
7	142.857	111.43	32.86	7.44	1.22	3.50	11.20
8	71.4286	278.57	16.43	9.74	2.51	3.50	15.20
9	71.4286	167.14	16.43	9.30	2.11	3.50	13.90
10	71.4286	55.71	16.43	5.02	0.94	3.30	8.50

Table22. Mean Irrigated Corn Yields by Irrigation Treatment for SDI as Simulated by EPIC

Irrigation Level mm	Mean Yield (tons/ha)	Standard Deviation (tons/ha)	Minimum Yield (tons/ha)	Maximum Yield (tons/ha)
113.03	6.72	1.77	3.50	11.20
197.80	8.09	1.82	4.40	12.70
282.58	9.21	1.96	4.50	13.60
367.35	10.20	2.14	4.50	13.80
452.12	10.94	2.28	4.50	14.20
565.15	11.49	2.43	4.60	15.20

Table23. Mean Irrigated Corn Yields by Irrigation Treatment for Center Pivot Sprinkler Irrigation as Simulated by EPIC

Irrigation Level mm	Mean Yield (tons/ha)	Standard Deviation (tons/ha)	Minimum Yield (tons/ha)	Maximum Yield (tons/ha)
113.03	6.32	1.65	3.30	11.10
197.80	7.63	1.71	3.90	12.50
282.58	8.71	1.92	3.90	13.50
367.35	9.61	2.16	4.00	13.80
452.12	10.31	2.40	4.00	14.10
565.15	10.83	2.61	4.00	15.20

APPENDIX G—AMMONIA VOLATILIZATION PERCENTAGE

One of the issues concerning ammonia volatilization is whether the level of volatilization differs according to the source of nitrogen: effluent or urea. The ammonia volatilization data simulated in EPIC were not broken into these two sources. Regression analysis was used to estimate the percentage of ammonia volatilization from each nitrogen source. The underlying assumption of this analysis is that the ammonia volatilized either comes from urea or effluent or both. Thus

$$TV_t = TVE_t + TVU_t, \tag{G.1}$$

where TV_t is total ammonia volatilization, TVE_t is total ammonia volatilization from effluent and TVU_t is total ammonia volatilization from urea. Equation E.1 can be rewritten as

$$\frac{TV_t}{TN_t} = \frac{TVE_t}{TN_t} + \frac{TVU_t}{TN_t}, \tag{G.2}$$

where TN_t denotes total nitrogen applied from effluent or urea or both. Then consider TNE_t as total nitrogen applied from effluent and TNU_t as total nitrogen applied from urea and rewrite it as

$$\frac{TV_t}{TN_t} = \frac{TVE_t}{TN_t}\frac{TNE_t}{TNE_t} + \frac{TVU_t}{TN_t}\frac{TNU_t}{TNU_t}. \tag{G.3}$$

Rearranging terms yields

$$\frac{TV_t}{TN_t} = \frac{TNE_t}{TN_t}\frac{TVE_t}{TNE_t} + \frac{TNU_t}{TN_t}\frac{TVU_t}{TNU_t}, \tag{G.3}$$

which can be rewritten as

$$\frac{TV_t}{TN_t} = \Sigma_E \frac{TVE_t}{TNE_t} + \Sigma_U \frac{TVU_t}{TNU_t}, \tag{G.4}$$

where Σ_E represents the percentage of total nitrogen applied as effluent and Σ_U represents the percentage of total nitrogen applied as urea. Since we only consider effluent and urea as the sources of nitrogen, we clearly have that

$$\Sigma_E + \Sigma_U = 1; \tag{G.5}$$

and thus

$$\frac{TV_t}{TN_t} = \left(1 - \Sigma_U\right) \frac{TVE_t}{TNE_t} + \Sigma_U \frac{TVU_t}{TNU_t} \tag{G.6}$$

$$\Leftrightarrow \frac{TV_t}{TN_t} = \frac{TVE_t}{TNE_t} + \left(\frac{TVU_t}{TNU_t} - \frac{TVE_t}{TNE_t} \right) \Sigma_U \tag{G.7}$$

$$\Leftrightarrow \frac{TV_t}{TN_t} = \beta_0 + \beta_1 \Sigma_U . \tag{G.8}$$

The above regression can be estimated using OLS in SAS. The SAS results for center pivot sprinkler irrigation are reported in Table 24.

Table24. Percentage Ammonia Volatilization According to Nitrogen Source Regression Parameter Estimates for EPIC Simulated Data for Center Pivot Sprinkler Irrigation Computed with SAS Procedure REG

Variable	Parameter	Parameter Estimate	t-value	p-value
Intercept	β_0	0.23904 (0.0002576)	927.94	<0.0001
Σ_U	β_1	-0.07567 (0.0006092)	-124.21	<0.0001

Notes: Number of observations 3780, R-Square 0.8033

The percentage ammonia volatilization from effluent is given by the intercept and its estimate is 0.2390. The percentage ammonia volatilization from urea is given by the sum of the intercept and the slope parameters and its estimate is 0.1634. The estimate of its standard error is 0.021721, which can be obtained as follows:

$$\operatorname{var}\left(\hat{\beta}_0+\hat{\beta}_1\right)=\operatorname{var}\left(\hat{\beta}_0\right)+\operatorname{var}\left(\hat{\beta}_1\right)+2\operatorname{cov}\left(\hat{\beta}_0,\hat{\beta}_1\right) \tag{G.9}$$

$$\operatorname{var}\left(\hat{\beta}_0+\hat{\beta}_1\right)=0.0002576^2+0.0006092^2+2\left(-0.000000107445\right) \tag{G.10}$$

The SAS results for subsurface drip irrigation are reported in Table 25.

Table25. Percentage Ammonia Volatilization According to Nitrogen Source Regression Parameter Estimates for EPIC Simulated Data for SDI Computed with SAS Procedure REG

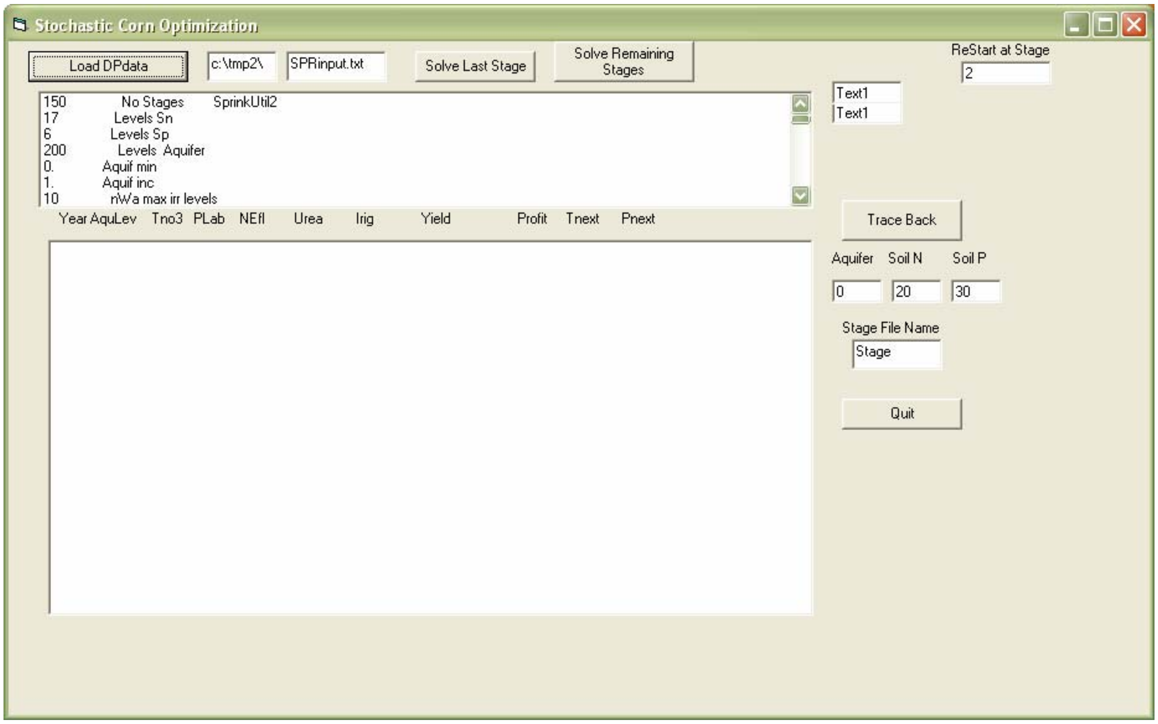
Variable	Parameter	Parameter Estimate	t-value	p-value
Intercept	β_0	0.08455 (0.00006951)	1216.29	<0.0001
Σ_U	β_1	0.01574 (0.00016767)	93.89	<0.0001

Notes: Number of observations 3780, R-Square 0.70.

For SDI, the estimate of percentage of ammonia volatilization from effluent is 0.0846 and the estimate of percentage of ammonia volatilization from urea is 0.10029 (standard error estimate is 0.000130333).

APPENDIX H—STOCHASTIC OPTIMIZATION APPLICATION

The application used to solve the stochastic dynamic optimization was written in Microsoft Visual Basic. The Visual Basic code sets up the problem and then calls a nonlinear optimization algorithm by Frontline Systems, Inc. included in the Dynamic Link Library Version 3.5 solver package. Figure 46 illustrates the interface of the application



c:\tmp2\

SPRinput.txt

ReStart at Stage: 2

Text1

Text1

```
150            No Stages      SprinkUtil2
17            Levels Sn
6            Levels Sp
200            Levels  Aquifer
0.          Aquif min
1.          Aquif inc
10            nWa max irr levels
```

```
Year AquLev  Tno3  PLab  NEfl    Urea    Irig      Yield        Profit  Tnext   Pnext
```

Aquifer: 0

Soil N: 20

Soil P: 30

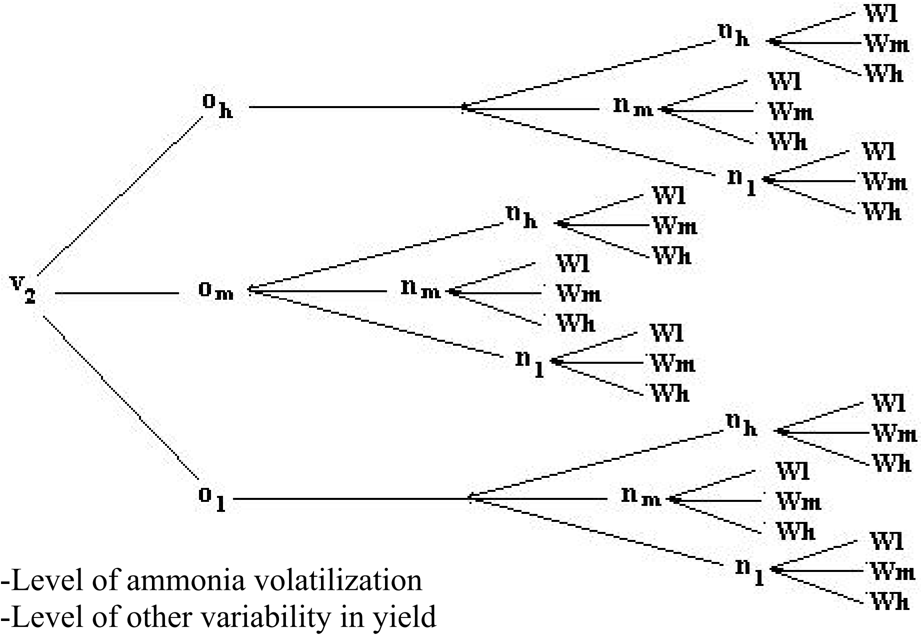
Stage File Name: Stage

Figure 45. Interface of Visual Basic Application, which Calls the Nonlinear Optimizer Included in the DLL Solver Package from Frontline Systems, Inc.

The optimization takes slightly less than 3 minutes per year considered in the planning horizon on a Pentium 4 personal computer with 2.73 GHz processing speed and

2 GB of RAM. For convergence purposes, the stochastic optimizations ran for at least 110 years.

The optimization procedure follows a probability tree similar to that shown in Figure 46. There are four possible levels of ammonia volatilization, three levels of other variability in irrigated corn yield, three levels of soil nitrogen, and three levels of possible dry-land wheat outcomes each with an associated probability. Each of these outcomes has assigned a probability. Each level of ammonia volatilization would have a similar probability tree.



Legend:
V-Level of ammonia volatilization
O-Level of other variability in yield
n -Level of soil nitrogen
W-Level of dry land wheat
Subscripts refer to low, medium, and high

Figure 46. Schematic of Partial Probability Tree Used in Stochastic Dynamic Optimization Program

APPENDIX I—OTHER COSTS USED IN STUDY

Table 26.Irrigated Corn Partial Budget (Excludes Irrigation Costs)

	Units	Price/Unit	Quantity	$/Acre
Production				
Corn	Bu.	$2.59	200	$518
Other Income	Acre	$56.78	1	$56.78
Total Receipts/Acre				**$574.78**
Operating Inputs				
Corn Seed	Acre	$35.20	1	$35.20
Fertilizer	Acre	$33.31	0	
Custom Harvest	Acre	$-	0	$-
Pesticide	Acre	$28.54	1	$28.54
Crop Insurance	Acre	$7.83	1	$7.83
Annual Operating Capital	Dollars	8.80%	94.2	$8.29
Machinery Labor	Hrs.	$6.50	1.5	$9.75
Irrigation Labor	Hrs.	$6.50		$-
Custom Hire	Acre	$-	0	$-
Machinery Fuel, Lube, Repairs	Acre	$24.73	1	$24.73
Irrigation Fuel, Lube, Repair	Acre	$104.85	0	$-
Rent	Acre	$-	0	$-
Other Expense	Acre	$-	0	$-
Total Operating Costs/Acre				**$114.34**
Fixed Costs				
Machinery				
Interest at	Dollars	9.10%		$36.98
Taxes at	Dollars	1.00%		$8.72
Insurance	Dollars	0.60%		$4.43
Depreciation	Dollars			$57.05
Land				
Interest at	Dollars	0.00%		$-
Taxes at	Dollars	0.00%		$-
Total Fixed Costs/Acre				**$107.18**
Total Fixed Plus Operating Costs/Acre				**$221.52**
Total Fixed Plus Operating Costs/ha				**$547.15**

Irrigation Fixed Costs are reported in separate appendixes.

Table 27. Dry-Land Wheat Budget

	Units	Price/Unit	Quantity	$/Acre
Production				
Wheat	Bu.	$3.23	25	$80.75
Small Grain Pasture	Acre	$22.00	1	--
Other Income	Acre	$14.50	1	$14.50
Total Receipts/Acre				**$95.25**
Operating Inputs				
Wheat Seed	Bu./acre	$6.00	2.00	$12.00
Fertilizer	Acre	$14.03	1	$14.03
Custom Harvest	Acre	$16.83	1	$16.83
Pesticide	Acre	$1.50	1	$1.50
Crop Insurance	Acre	$2.10	1	$2.10
Annual Operating Capital	Dollars	.80%	38.64	$3.40
Machinery Labor	Hrs.	$6.50	1.26	$8.19
Irrigation Labor	Hrs.	$-	0	$-
Custom Hire	Acre	$-	0	$-
Machinery Fuel, Lube, Repairs	Acre	$15.20	1	$15.20
Irrigation Fuel, Lube, Repair	Acre	$-	0	$-
Rent	Acre	$-	0	$-
Other Expenses	Acre	$-	0	$-
Total Operating Costs/Acre				**$73.25**
Fixed Costs				
Machinery				
Interest at	Dollars	9.10%		$13.89
Taxes at	Dollars	1.00%		$4.25
Insurance	Dollars	0.60%		$1.65
Depreciation	Dollars			$20.00
Land				
Interest at	Dollars	0.00%		
Taxes at	Dollars	0.00%		
Total Fixed Costs/Acre				**$39.79**
Total Costs(Oper.+Fixed)/Acre				**$113.04**
Returns above Total Costs/Acre				**($17.79)**
Returns above Total Costs/Ha				**($43.94)**

Table 28. Cost of Extracting Water from Aquifer

	Unit	SDI	CPS
Maximum unit cost of pumping water from aquifer (C^m)	\$/m^3	620.39	636.14
Unit value of water extracted (C^w)	\$/m^3	-3.96949	-3.22681

Table 29. Other Parameters Used in Model

	Unit	Value
Cost of effluent (valued as nitrogen)	\$/kg	\$0.158
Price of corn	\$/mt	\$102.36
Value of water in the aquifer	Farm	\$167,995
Value of land as dry land	Farm	\$224,000

Table 30. Matrix of Dry-Land Wheat Net Return Outcomes and Probabilities

Outcome	Unit	Net Return	Probability
Low Return	\$/ha	(\$19.37)	0.262
Medium Return	\$/ha	\$52.03	0.476
High Return	\$/ha	\$111.31	0.262

VITA

Rita Isabel Rodrigues Carreira

Candidate for the Degree of

Doctor of Philosophy

Thesis: ECONOMIC STUDY OF ALTERNATIVE BEST MANAGEMENT PRACTICES FOR SWINE EFFLUENT APPLICATION TO CORN IN SEMIARID CLIMATE

Major Field: Agricultural Economics

Biographical:

Personal Data: Born in Coimbra, Portugal, on May 3, 1972, the daughter of Victor Carreira and Maria Fernanda da Velha.

Education: Graduated from Escola Secundária de Jaime Cortesão, Coimbra, Portugal in July 1990; received Bachelor of Science degree from Universidade de Coimbra, Portugal in October, 1996; received Masters of Science degree from Oklahoma State University in May 2000. Completed the requirements for the Doctor of Philosophy degree with a major in Agricultural Economics and a minor in Statistics at Oklahoma State University in December, 2004.

Experience: Graduate Research Assistant, Department of Agricultural Economics, Oklahoma State University, February 1998 to May 2000. Teaching Practicum in AGEC 5503 Economics of Natural and Environmental Policy, Department of Agricultural Economics, Oklahoma State University, Fall 2001. Teaching Assistant for AGEC 5213 Econometric Methods, Department of Agricultural Economics, Oklahoma State University, Spring 2003. Doctoral Research Assistant, Department of Agricultural Economics, Oklahoma State University, June 2000 to May2004. Research Associate, Department of Agricultural Economics and Agribusiness, University of Arkansas, June 2004 to present.

Professional Memberships: American Agricultural Economics Association, Western Agricultural Economics Association, Southern Agricultural Economics Association.

Name: Rita Isabel Rodrigues Carreira Date of Degree: December 2004

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: ECONOMIC STUDY OF ALTERNATIVE BEST MANAGEMENT PRACTICES FOR SWINE EFFLUENT APPLICATION TO CORN IN SEMIARID CLIMATE

Pages in Study: 129 Candidate for the Degree of Doctor of Philosophy

Major Field: Agricultural Economics

Scope and Method of Study: The intent of this study was to analyze the economic implications of alternative irrigation systems (subsurface drip water irrigation and center pivot sprinkler irrigation) in Texas County, Oklahoma, a region facing a finite water supply that is declining rapidly and where swine production has rapidly increased in the past 14 years leading to population concerns because of the large amount of swine effluent produced. The basis for the comparison between the two systems was a representative section of land, with one of the quarter sections producing irrigated corn and the remaining sections produced dry-land wheat. The nutrient source for irrigated corn was swine effluent; the production horizon assumed was 100 years. After data were simulated in EPIC, econometric relationships were estimated for several equations: irrigated corn yield, soil nitrogen carryover, soil phosphorus carryover, and nitrogen percolation. A probability distribution for ammonia volatilization was also estimated. The objectives of the study were to evaluate both irrigation systems in terms of soil nutrient accumulation, irrigated corn yield, water use and aquifer life, and expected net revenues over the production horizon. Two types of analysis were performed to compare both systems: a deterministic dynamic programming optimization and a stochastic dynamic programming optimization.

Findings and Conclusions: The estimated relationships had parameters that were consistent which our initial expectations. Based on the results of this study and assuming that it captures producer preferences correctly, SDI is economically more competitive than center pivot irrigation for regions that have similar characteristics to Texas County, Oklahoma, even without considering the current monetary incentives given through the EQIP. The advantage of the SDI is not very big annually, but it is always positive. The lifetime of the aquifer is longest with center pivot as more area is irrigated with the SDI. Producers are advised to seriously consider the SDI as an alternative to CPS when irrigating in the Oklahoma Panhandle. Farmers as well as policy makers should also monitor phosphorus accumulation in soil when effluent is land applied, as the model projected that some accumulation should occur.

Advisor's Approval: Dr. Arthur L. Stoecker