Dynamic Comparison of Systems for Irrigation and Effluent Application

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Abstract

This study compares subsurface drip irrigation and sprinkler irrigation with respect to expected returns, aquifer life, nutrient utilization and accumulation in the production of irrigated corn using swine effluent and fresh groundwater from a depleting aquifer in the Oklahoma Panhandle. The results of the Dynamic Programming model indicate that SDI outperforms center pivot sprinkler irrigation in terms of NPV of net returns and reduced phosphorus accumulation in soil. Soil nitrogen accumulation in soil is greater with SDI. Groundwater depletion is projected to occur at the end of 36th year with center pivot irrigation.

Selected paper prepared for presentation at the Southern Agricultural Economics Association Annual Meeting, Tulsa, Oklahoma, February 14-18, 2004

This paper is a draft and includes preliminary results.
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Introduction

Texas County, located in the Oklahoma Panhandle, faces semiarid climate and it is common for years of drought to be followed by several years of above normal rainfall. The absence of a great body of water in the area causes temperatures to reach extreme low cold in the winter and intense heat in the summer (Kromm, D. E. and S. E. White. 1992a). Water is a valuable commodity in the region since rainfall is inadequate and does not meet crop requirements (Lindley, 1999). The main crop products of Texas County, Oklahoma, are sorghum, wheat, hay, and corn. Corn and sorghum are important feed components in swine production. The region is one of the highest concentrated animal production areas in the United States (Lindley, 1999). The expansion of large swine concentrated animal feeding operations in Oklahoma, and particularly in this county, started in 1991 after the Oklahoma Senate passed bill 518 (April 3, 1991), which eased restrictions against corporate farming.

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 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 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.

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 and efficient irrigation practices be developed in order to assist farmers and policy makers in making wise decisions in water management and environmental protection. This paper provides a treatment of both these problems in the context of sustainable agricultural practices. We compare two irrigation systems—subsurface drip irrigation, SDI, and center pivot sprinkler irrigation—in terms of their economic and environmental performance over a long term (100 years) planning horizon.

Water Use and Environmental Concerns

Most of the water used in crop irrigation and animal production is extracted from the Ogallala aquifer. The recharge of the aquifer is negligible compared to current extraction rates, and groundwater use in the area can be viewed as a mining activity (Stoecker, Seidman, and Lloyd, 1985; Howell, Schneider, Evett, 1998). Economic exhaustion will be achieved when "net returns per acre from dryland farming exceed net returns per acre from irrigation" (Harris, Mapp, and Stone, 1983). Current irrigation methods practiced in the county include furrow irrigation and sprinkler irrigation, neither 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 using swine effluent also pose drawbacks such as high rates of water evaporation and ammonia volatilization, soil erosion, and phosphorus runoff.

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. Subsurface drip irrigation systems have high capital cost but offer potential benefits from smaller and more precise applications of irrigation and effluent. More precise application of effluent means less volatilization of nitrogen and consequently lower phosphorus and salinity accumulation. These benefit the producer by reducing the variability of returns and increasing the number of years for irrigation and/or effluent application.

The objective of the present study is to improve available economic information regarding swine manure management and irrigation practices in corn production for the semiarid Oklahoma Panhandle. Specifically, this study identifies economically and environmentally sound practices regarding the effects of time and method of application of swine effluent on the crop's nutrient utilization.

Theoretical Development

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, and the possibility of phosphorus accumulation in the soil. In 1962, Bostwick (p. 49) 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[those which assume randomness], even though hidden in residual error terms." A Markov process assumes that the evolution of a variable from one state to the next follows probabilistic "laws of motion." (Hillier and Lieberman 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 a similar idea and showed that in the case of irrigation, 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 advancement of computer technology in recent years has made possible the use of more rigorous data in terms of accuracy and detail in agronomic research.

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

$$\max NPV = \sum_{t=1}^{T} \frac{\theta \cdot \left[P^c \cdot E(Y_t) - C^e \cdot F_t - \left(C^m - C^W \cdot W_t \right) \cdot G_t - OVC \right] + (1-\theta) \cdot R^w}{(1+r)^t}, \quad (1)$$

for each irrigation system, where P^c is the price of corn, $E(Y_t)$ 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 water used in irrigation, W_t is the quantity of water extracted from the aquifer, C^W is the unit value of the water extracted, C^m represents maximum unit cost of pumping aquifer. Pumping costs are set up so that they increase with the depth at which we have to extract the remaining freshwater from the aquifer. R^{w} represents the net revenue of growing wheat, and θ is the proportion of a quarter section of land producing corn (if we use a center pivot, $\theta = .7875$; for the SDI, $\lambda = 1$. The choice variables for the SDI system are quantity of water used in irrigation and quantity of effluent applied, for the center pivot sprinkler, we assume irrigation amount is constant and the choice variable is amount of effluent applied.

Assuming diminishing returns, the functional form for yield can be modeled as a modified Mitscherlich-Baule function, thus

$$\mathrm{E}\left(Y_t\right) = \eta_0 \left\{1 - \exp\left[\eta_1\left(SN_t + AN_t\right)\right]\right\}\left\{1 - \exp\left[\eta_2\left(SP_t + AP_t\right)\right]\right\}\left\{1 - \exp\left[\eta_3 + \eta_4 G_t\right]\right\}, \quad (2)$$

where $\eta_0, \ldots, \eta_4$ are the parameters to be estimated, SN_t is the level of nitrogen in the soil at year *t*, AN_t is the level of nitrogen applied, at year *t*; AP_t and SP_t are similarly defined for phosphorus. We assume at this point perfect substitutability between the nutrient in the soil and the application of that same nutrient to the plant. In the case of center pivot sprinkler irrigation, we assume that the term $\exp\left[\eta_3 + \eta_4 G_t\right]$ is not relevant for the optimization and thus is removed. The change in the amount of nitrogen carryover equation is defined as

$$E\left(SN_{t+1} - SN_t\right) = \lambda_0 + \lambda_1 AN_t + \lambda_2 AN_t^2 + \lambda_3 E\left(Y\right)_t + \lambda_4 K_t, \quad (3)$$

where K_t represent deep nitrogen percolation, which is very relevant in SDI but can be ignored in the sprinkler irrigation, thus $\lambda_4 = 0$ for this system. The parameters are not the same for both systems but the underlying hypothesis is that $\lambda_3 < 0$ and $\lambda_4 < 0$, while $\lambda_1 > 0$. The phosphorus carryover constraint is defined as

$$E\left(SP_{t+1}\right) = \delta_0 + \delta_1 SP_t + \delta_2 AP_t + \delta_3 E\left(Y\right)_t, \quad (4)$$

and we assume that $\delta_2 > 0$ and $\delta_3 < 0$. The water supply constraint is defined as

$$W_{t+1} = W_t - G_t. \tag{5}$$

In the case of SDI, the deep nitrogen percolation constraint is defined as

$$E\left(K_{t+1}\right) = \exp\left(\gamma_0 + \gamma_1 SN_t + \gamma_2 SN_t^2 + \gamma_3 AN_t\right), \tag{6}$$

we ignore this constraint in the sprinkler optimization. We also assume that $AN_t = \sigma F_t$ and $AP_t = (1-\sigma)F_t$, where σ is the proportion of nutrient value in the effluent that is nitrogen. In this case we are only interest in the nutrient value of effluent as either nitrogen or phosphorus.

Study Implementation

We 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, dependent on groundwater for irrigation. We assumed that the farm overlies the Ogallala aquifer; the distance to the bottom of the aquifer was 375 feet, the aquifer saturated area was 200 feet deep with a porosity of 25 percent and specific yield 22 percent. It was assumed that only 10 percent of the area was irrigated, thus there were 21.9 cubic meters of water for each squared meter of irrigated area. We 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 155 acres. Under irrigation with a center pivot sprinkler system we assumed 126 acres were cultivated with corn and the remaining area was cultivated in dryland wheat-fallow rotation. For the context of this study, irrigation uses a mixture of swine effluent and fresh groundwater. Due to data unavailability, irrigated corn yield were simulated in EPIC following a balanced experimental design, for a period of 100 years, and taking into account the statistical distributions of climatological variables in Texas County and using 10 different weather patterns which were randomly sampled from these distributions. Groundwater use, availability, and water quality data were obtained from the United States Geological Survey and Underground Water Conservation Districts. Climatological data were obtained from the National Oceanographic and Atmospheric Administration and from the Oklahoma Mesonet. Crop prices and production cost information were obtained from USDA publications.

The production area considered for the optimization procedure was a quarter section of land. The producer faces a constrained supply of fresh groundwater. In the long run, phosphorus accumulation in the soil may constrain the producer's activity. Current chemical analyses show that the soil in Texas County is not phosphorus saturated but there are studies that show that even phosphorus deficient soils become phosphorus saturated when they receive animal manure over long periods of time. Over time, as the soil becomes phosphorus saturated, the value of the phosphorus in the effluent will decline.

Results

The yield equations were estimated in SAS. We obtained starting values for the estimation of the yield function in Microsoft® Excel, which we then used to perform the nonlinear estimation in SAS procedure NLIN using the Gauss-Newton method. The results are reported in Table 1 for each irrigation system. The signs of the parameters were as expected. The estimate of η_0 for the SDI system is lower than for the center pivot irrigation system, which is interesting as this function is defined as converging to the intercept as the levels of nitrogen, phosphorus, and irrigation increase. One would expect the SDI system to have a higher estimate as effluent and water applications are more precise.

The estimates for the nitrogen carryover equation were computed in SAS proc GLM and are reported in Table 2. The estimate for deep nitrogen percolation indicated that this variable is a significant determinant of soil nitrogen removal in the SDI system. All the estimates had expected signs. The R-square for the sprinkler system was very low compared to SDI system, which indicates that the previous year's level of nitrogen in the soil is a very good indicator of this year's level. The phosphorus carryover equation parameter estimates were computed in proc GLM and are reported in Table 3. In both irrigation systems the most important determinant of soil phosphorus is the previous year's soil phosphorus level.

As indicated by the nitrogen carryover equation, deep nitrogen percolation is a very important variable in the SDI irrigation. Thus we estimated an equation for this variable for the SDI system in SAS proc GLM. The estimates are reported in Table 4. According to these estimates, and as expected, deep percolation of nitrogen increases with as the level of soil nitrogen and the nitrogen application level increase. This equation allows to keep track of annual percolation in the optimization model.

The results of the optimization conducted in GAMS using a 5 percent discount rate indicate that the NPV of the expected net returns of farming with the SDI system over a period of 100 years is greater than that of center pivot irrigation ($9,550.51/ha vs. $7,112.39/ha). The difference is due to the mining out effect as with the center pivot sprinkler system, freshwater from the aquifer runs out by year 36 (Figure 4), at which point one must revert to dryland wheat farming, a less profitable venture. However, this spread is lower if one considers the higher fixed costs of SDI. Presently, farmers can obtain an incentive to adopt SDI through the Environmental Quality Incentives Program, which will refund up to 50 percent cost share payment of the system, which reduces the cost of adopting SDI.

In terms of irrigation level, we held irrigation level constant at roughly 0.6 m/ha in the case of center pivot sprinkler irrigation; irrigation level was considered variable for the SDI. As can be seen in Figure 1, the optimal irrigation level with SDI declines over time until it reaches its lower bound, which was set a 0.2 m/ha . The optimal nutrient in effluent level for sprinkler irrigation was at the upper bound, which was set at 300 kg/ha for the lifetime of corn production; for SDI, the first 14 years have the upper bound as the optimal effluent level after which, the level of effluent applied declined steadily (Figure 2). Irrigated corn yield level is significantly higher for sprinkler irrigation than it is for SDI as can be seen in Figure 3, which is due to the lower irrigation level and also to the decline in effluent level applied.

The amount of nitrogen in the soil increases steadily with both systems but with the sprinkler it increases at a lower rate (Figure 5). This outcome has to do with the lower level of ammonia volatilization with the SDI. On average, ammonia volatilization was 8 percent for the SDI and 24 percent for the center pivot sprinkler irrigation. Deep nitrogen percolation reduces the amount of nitrogen in the root zone, where it can be available for plant use. It is of concern because nitrogen leaching may contaminate the subsurface water table. In areas such as the Oklahoma Panhandle, the water table is located deep enough that nitrogen contamination of the aquifer is not very likely. Nonetheless, to assess this concern, deep nitrogen percolation was considered variable for the SDI model. Its projected level over time is depicted in figure 6, from this figure we can see that it follows a bell shaped curve, which peaks at about 1.8 kg/ha. Thus nitrogen percolation eventually declines as less effluent and water are applied to the crop.

The level of soil phosphorus is higher with center pivot sprinkler irrigation than with SDI (Figure 7) , which agrees with our expectations that SDI would be a better system for managing phosphorus accumulation in soil.

Conclusions and Study Limitations

It was the intention of this study to model farming in a semiarid region, taking into account weather uncertainty, animal effluent use, and a depleting freshwater aquifer as the source of irrigation water, over a long period of time. At this point, the results presented in this paper draft do not include the stochastic analysis, which is still underway. As expected, our preliminary results show that SDI allowed for longer longevity of aquifer and less soil phosphorus accumulation, which were two of the environmental concerns focused in this study. Although soil nitrogen accumulation in the soil occurs at a higher rate with the SDI system, deep nitrogen percolation does not seem to be of great concern over the 100 year period. Despite the higher irrigated corn yield made possible with center pivot irrigation, the SDI system performs better than sprinkler irrigation in terms of NPV of net returns.

Appendix I: Tables

Table 1. Irrigated Corn Yield Function Parameter Estimates Computed with the Gauss-Newton Method in SAS Proc NLIN

		Parameter Estimates	
Variable	Symbol	SUBSURFACE DRIP IRRIGATION	Center Pivot Sprinkler Irrigation
	η_0	13.6648	14.5234
		(0.2328)	(0.0748)
Nitrogen	η_1	-0.0183	-0.00711
		(0.00103)	(0.00009)
Phosphorus	η_2	-0.0674	-0.0545
		(0.00336)	(0.00388)
	η_3	0.1574	--
		(0.1859)	
Irrigation	η_4	-0.5146	--
		(0.0718)	

Values in parenthesis refer to approximate standard errors of parameter estimates. Models MSE estimates were 1.2252 for SDI and 1.2106 for center pivot. For SDI *N*=6,300, for center pivot *N*=5,940.

Table 2. Nitrogen Carryover Equation Parameter Estimates Computed with the SAS Proc GLM

		Parameter Estimates	
Variable	Symbol	Subsurface Drip Irrigation	Center Pivot Sprinkler Irrigation
Intercept	λ_0	1.23735	0.390126
		(14.98)	(3.76)
AN_t	λ_1	0.05202	0.061129
		(33.46)	(22.56)
AN_t^2	λ_2	-0.00003	-0.000113
		(-9.41)	(-13.20)
$E(Y)_t$	λ_3	-0.08245	-0.596202
		(-74.30)	(-39.63)
K_t	λ_4	-0.04358	
		(-1.69.76)	

Values in parenthesis refer to t-values of parameter estimates. R-square was 0.8603 for SDI and 0.2266 for center pivot. For SDI *N*=5,940, for center pivot *N*=5,940.

Table 3. Phosphorus Carryover Equation Parameter Estimates Computed with the SAS Proc GLM

		Parameter Estimates	
Variable	Symbol	Subsurface Drip Irrigation	Center Pivot Sprinkler Irrigation
Intercept	δ_0	-2.86668	-1.14058
		(-15.16)	(-0.85)
SP_t	δ_1	0.54821	0.84738
		(80.53)	(125.15)
AP_t	δ_2	0.02862	0.92015
		(5.99)	(14.80)
$E(Y)_t$	δ_3	0.47613	-0.92006
		(17.18)	(-3.53)

Values in parenthesis refer to t-values of parameter estimates. R-square was 0.6976 for SDI and 0.9137 for center pivot. For SDI *N*=5,940, for center pivot *N*=5,940.

Table 4. Nitrogen Percolation Equation Parameter Estimates Computed with the SAS Proc GLM

		Parameter Estimates	
Variable	Symbol	Subsurface Drip Irrigation	Center Pivot Sprinkler Irrigation
Intercept	γ_0	-2.52763	--
		(-23.23)	
SN_t	γ_1	0.04788	--
		(13.26)	
SN_t^2	γ_2	-0.00024	--
		(-9.28)	
AN_t	γ_3	0.00378	--
		(5.01)	

Values in parenthesis refer to t-values of parameter estimates. R-square was 0.2057 *N*=5,940.

Appendix II: Figures

Figure 1. Irrigation Level Predicted in GAMS

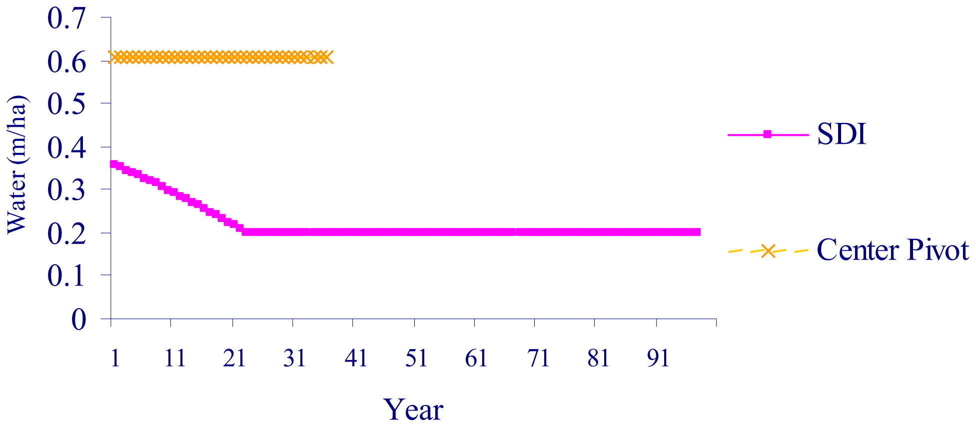


Figure 2. Nutrient in Effluent Application Predicted in GAMS

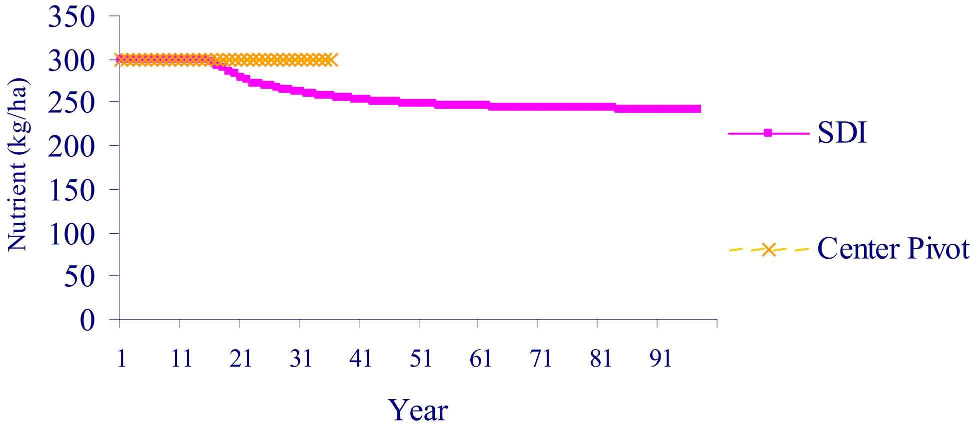


Figure 3. Irrigated Corn Yield Predicted in GAMS

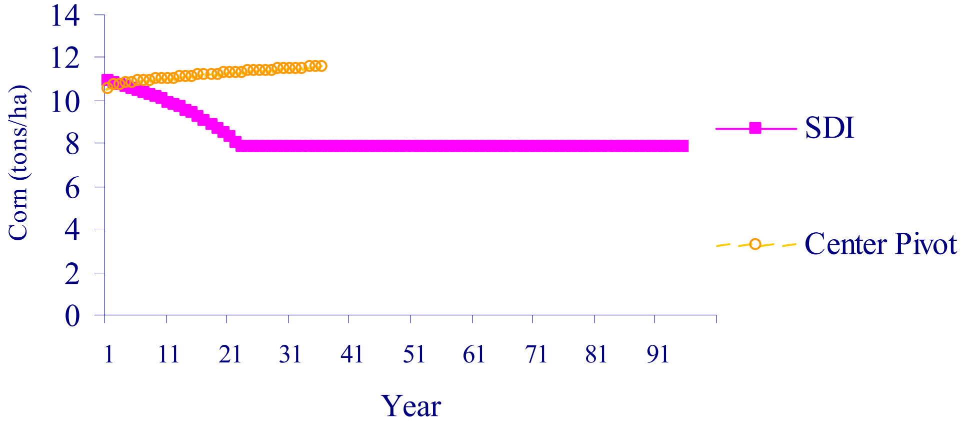


Figure 4. Remaining Water Supply Predicted in GAMS

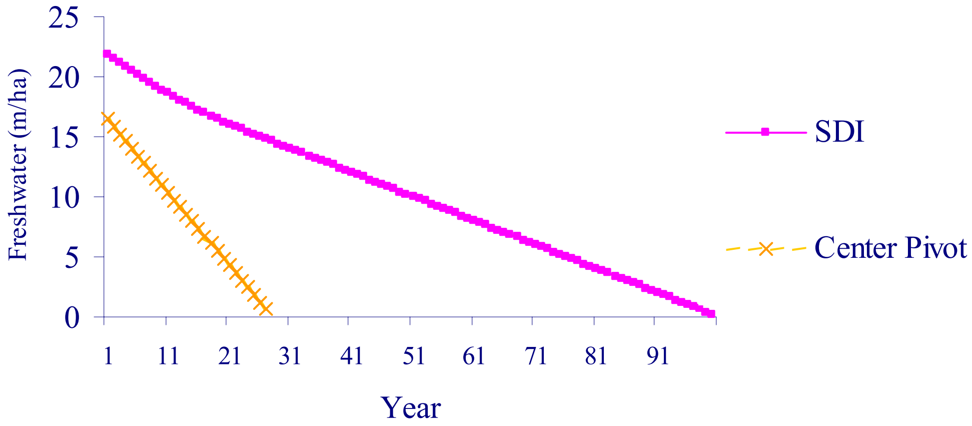


Figure 5. Soil Nitrogen Accumulation Predicted in GAMS

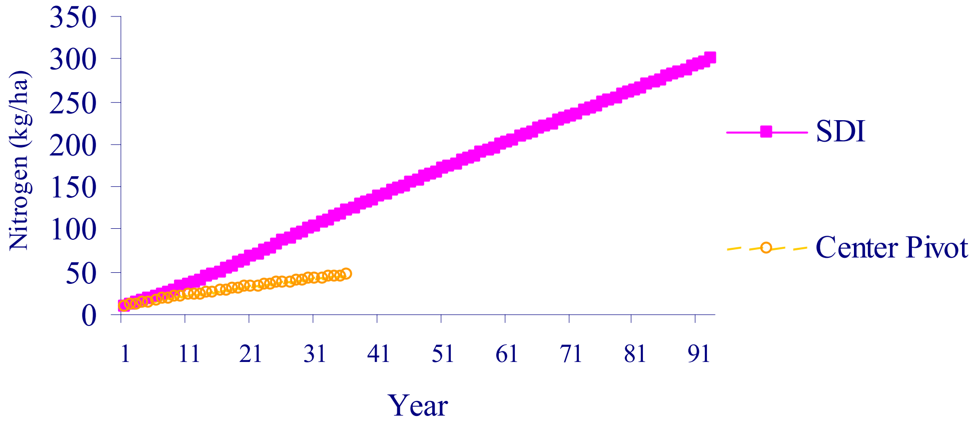


Figure 6. Ammount Nitrogen Percolation Predicted in GAMS

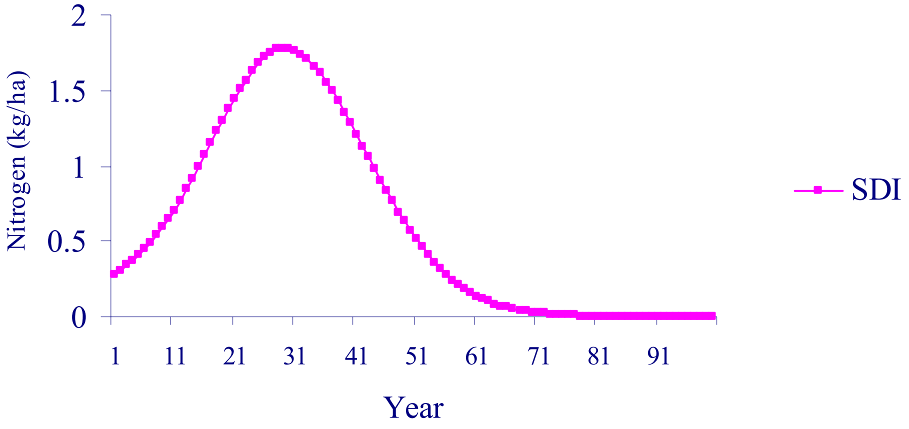
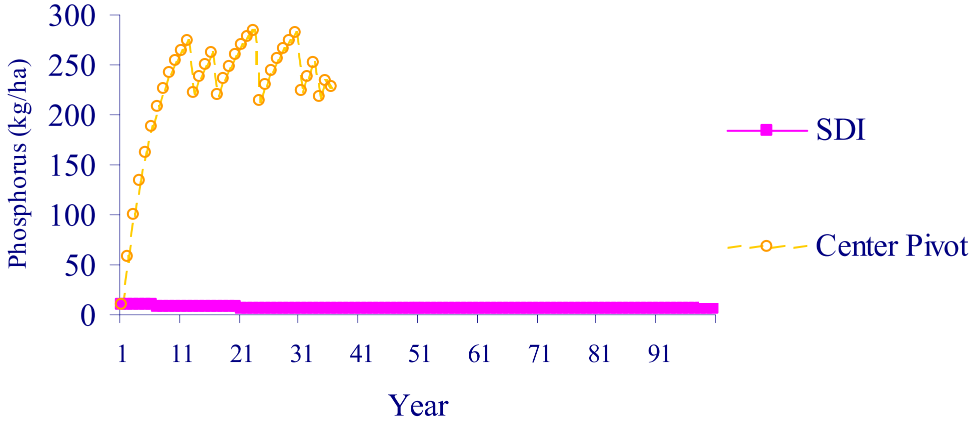


Figure 7. Soil Phosphorus Accumulation Predicted in GAMS



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