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Subsurface Drip Irrigation Versus Center-Pivot Sprinkler for Applying Swine Effluent to Corn

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A risk-averse irrigated corn producer would be better off choosing the more expensive subsurface drip irrigation (SDI) over center-pivot sprinkler (CPS), given limited aquifer life and swine effluent and urea fertilization. A stochastic optimization using EPIC data maximized expected utility of 100 years' worth of net revenues for a quarter section. Phosphorus accumulation was more likely with the CPS than with the SDI but soil nitrogen was constant under both systems. SDI conserves more water than CPS per acre but depletes the aquifer faster because a greater area is irrigated. These results were invariant in the sensitivity analysis.

Key Words: aquifer depletion, center-pivot sprinkler irrigation, certainty equivalent, corn irrigation, mathematical programming, risk, stochastic optimization, subsurface drip irrigation

JEL Classifications: C61, C65, Q12, Q30, Q53

During the 1990s, animal feeding operations, including swine operations, became highly consolidated and geographically concentrated enterprises (Sweeten, Miner, and Tengman 2003). Usually, large swine concentrated animal feeding operations (CAFOs) locate in agricultural areas where there is an abundant supply of corn and sorghum, which are important feed components in swine production (Forster). Such is the case of Texas County, OK, which in 2002 had 1.07 million hogs and pigs, almost half of the 2.25 million in the state (U.S. Department of Agriculture–National Agricultural Statistics Service [USDA–NASS]). For that same year, the U.S. hog and pig population level was estimated at 60.4 million (*ibid.*). Animal production and their products are extremely important for Oklahoma agriculture. Eighty-two percent of the market value of agricultural products sold in the state in 2002 was from livestock, poultry, and their products (this percentage corresponds to $3.6 b.); in Texas County the percentage was even higher, about 92%, which corresponds to $609.1 m.

After the Oklahoma Senate passed regulations easing restrictions against corporate farming in 1991, there was an 8,130% increase in the number of hogs and pigs in Texas County between 1992 and 2002 (USDA–NASS). Although the county regained new economic life with the installation of the new swine operations, by 1998 there was controversy regarding the disposal of swine manure, and a temporary moratorium was imposed to limit

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construction and expansion of hog farms in Oklahoma (Hinton).

Froese estimates that a growing/finishing pig produces on average 0.28 cubic feet of manure per day. Ribaudo et al. estimated that, in 1998, there were 28.2 animal units per acre of land receiving manure in Oklahoma farms. Annually, the larger swine unit facilities located in semiarid regions can produce as much as three million gallons of lagoon effluent, according to ongoing research at Oklahoma State University. Because CAFOs produce such large amounts of manure, nearby land may be insufficient to use all the manure in a sustainable manner (Sweeten, Miner, and Tengman); this is especially true if effluent is applied using a phosphorus-based standard. According to Ribaudo et al., who used data from the 1998 ARMS hog survey, large animal farms in Oklahoma would need an additional 600 acres on average to apply manure following an N-based standard; for a P-based standard, an additional 1,253 acres would be required. The 1998 practice for farms with more that 1000 animal units was to apply manure on 139.4 acres on average (*ibid.*). Transporting the manure off-site is costly, and total cost to transport a ton increases with distance shipped. The great volume of manure produced usually needs to be contained in treatment or in storage facilities before it can be land-applied. Tyson provides an explanation of different facilities and the advantages each provides; he also alerts that problems related to odor and environmental quality can be mitigated if one devotes enough thought to planning and choosing an adequate facility type and size. In Oklahoma, Ribaudo et al. estimated that 89.1% of the swine farms use lagoons instead of slurry systems to manage manure.

The practice of land-applying animal manures dates back many centuries. Although it is commonplace to say that manure application is beneficial to the soil, some of the chemical processes that take place in some soils are not fully understood. Some studies have shown that manure benefits soils by maintaining soil pH and by enhancing soil quality through the provision of necessary nutrients such as nitrogen, phosphorus, and potassium (Zhang and Hamilton). The practice is sustainable in the long term if the nutrient application rate does not exceed the nutrient removal rate; otherwise problems such as phosphorus accumulation in soil, increased soil salinity, and nutrient runoff can occur (Zhang and Hamilton; Sharpley et al.).

Most effluent application uses an irrigation system. Great care must be spent flushing the irrigation system to prevent clogs that, if left unattended, can shorten or threaten system life (Lamm et al.). In a setting where irrigation water is a finite resource, effluent application can only last while water irrigation is economically feasible, that is, while the benefits of using the water exceed the costs of extracting and using it. In places such as Texas County, effluent application is much more than a disposal issue, since water scarcity is such a threat that water reutilization is a necessity.

When using animal manure to fertilize crops, one must also consider the fate of the nutrients in manure during the application. Nitrogen is a critical nutrient in crop production, especially corn, but it is very volatile. Hence, when manure is land-applied, nitrogen may volatilize into the atmosphere in the form of ammonia. The application of swine effluent using subsurface drip irrigation (SDI) results in less ammonia volatilization (as well as less water evaporation during irrigation) than center-pivot sprinkler (CPS) irrigation. But these savings come at a cost. The initial investment cost of a CPS is less than half the cost of an SDI system and the CPS could have some residual value, whereas the SDI has little to none. However, for a given square field the SDI will allow a greater proportion of the field to be irrigated than the CPS, as the latter system only irrigates circular areas. For example, irrigating a quarter section of land using a CPS involves irrigating a half-mile diameter circle with an approximate area of 126 acres and leaving the corners (the remaining 34 acres) of the quarter section under dry land. Although center pivots can be modified to cover the whole quarter section, these modifications add about 25% to the cost of the system. In the region of the study, the modification is not common and not cost effective. Because efflu-

ent application with the SDI is more precise, higher corn yields should be obtained (Camp; Phene and Phene). The crucial question is whether the irrigation savings combined with the higher yield potential of the SDI are enough to outweigh the cost difference between the two systems given a finite water supply. If one assumes effluent application as a nutrient source, a finite water supply implies that swine effluent application to crops is also a finite resource, since we assume that effluent is only applied as long as irrigation is taking place.

Texas County, which is located in the Oklahoma Panhandle, has a semiarid climate. From 1948 to 2002, the average annual precipitation was less than 17 inches, according to data collected from the National Climatic Data Center, the Oklahoma Mesonet, and the Oklahoma Climatological Survey. Most of the water used in swine production and crop irrigation in Texas County is extracted from the Ogallala aquifer, which is a groundwater formation created millions of years ago that has been an important water source for much of the High Plains of the United States. The aquifer receives little to no recharge and its saturated depth is quite variable. For example, parts of Nebraska hold enough water reserves to last over 400 years at current levels of use, while other areas have been depleted.

The intensive nature of animal and crop production in Texas County paired with the issue of nonrenewability of the water supply triggers some interesting questions. Kromm and White wonder whether it is reasonable to deplete a nonrenewable resource to produce agricultural products in a time of plenty. Another related issue is whether farmers should switch to water-conserving technologies, such as SDI, that could be more costly, or whether they should continue using current irrigation technologies.

The purpose of this analysis is to compare two irrigation systems (SDI and CPS) in the production of irrigated corn over a long-term setting. Swine effluent is assumed to be applied to corn as a source of nitrogen, potassium, and phosphorus. The choice variables are the amount of irrigation and effluent to apply to corn cultivated on a 160-acre square field (quarter section) located in Texas County, assuming a finite water (and effluent) supply and a 100-year production horizon. The area cultivated with irrigated corn under the SDI is 155 acres (assuming that 5 acres of the quarter section are lost to turn rows). When irrigating with the CPS, we assume that a 126-acre circle is cultivated with irrigated corn and the remaining area in the corners of the quarter section (34 acres) that is not reached by the CPS are kept in dry land and cultivated in a dry land wheat-fallow rotation. We assume the ratio of irrigated area to extraction area is 20%; we use the term extraction area to refer to the underground area created by the cone of depression of the well. The current Oklahoma legislative framework assigns ownership of underground water to whomever extracts it; however, extraction must comply with a permit system, which ensures a minimum aquifer life of 20 years. We also assume that the farm includes 480 acres cultivated with dry land wheat, which lowers the farmer's fixed cost per acre and ensures that no competing wells affect well yield. Since farms in Texas County are traditionally large, it would have been unrealistic to limit farm size to the irrigated quarter section. A discrete probability distribution was computed to represent the variability of dry land wheat revenues.

The comparison between the two irrigation systems is done by maximizing the expected utility of the stream of net revenues of the farm assuming one of the quarter sections is irrigated under each system. We use a power utility function to compute the expected utility levels and then compute a stream of certainty equivalents of the net revenues for each irrigation system, that is, the level of income the producer is willing to receive each year to not face any risk. Since we assume a risk-averse producer, the certainty equivalent is always less than the level of net revenue that maximizes expected utility each year. We compute the present value (PV) of the certainty equivalents and of the net returns. The difference between the PV of the certainty equivalents and the PV of the utility maximizing net revenue represents the amount of money that the producer

is willing to give up to avoid risk; this difference is also known as the risk premium.

Theoretical Considerations and Model

Several studies have compared SDI and CPS using a budget approach (Dumler and Rogers; O'Brien et al. 1998, 2003); although budgeting is a necessary part of any study, the present problem requires a more comprehensive 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.

Saghaian, Dillon, and Salim simulated crop yields with a biophysical simulation model under no irrigation, variable rate subsurface irrigation, and uniform rate subsurface irrigation and concluded that uniform rate irrigation outyielded the other two strategies. They did not compare SDI with other irrigation systems, thus from their conclusions it cannot be determined whether farmers using CPS should switch to SDI.

In 1962, Bostwick proposed that crop yield be modeled as a Markov process because the distribution of the observed data is not random. A Markov process assumes that the evolution of a variable from one state to the next follows probabilistic "laws of motion" (Hillier and Lieberman). For example, this year's yield and this year's decision choices will determine a probabilistic distribution for next year's 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 is often associated with variability of yield and 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 of irrigation: 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). Simulation programs such as EPIC, if properly calibrated to local climate and soil, can be used to generate agronomic data representative of certain management practices. Dynamic programming and the construction of stochastic models, such as Markov processes that consider climatological patterns, has become easier with current computing technology.

Once a crop has been planted, there are several ways that one can influence yield, including irrigation level, application efficiency of the irrigation system, and nutrient application. By tinkering with some of these decision variables the farmer can reduce yield variability, which can be traced to factors such as physical soil differences, seed quality variability, and atmospheric conditions. The question in a dynamic setting lies in choosing how much to apply, how to apply, and when to apply so that the farmer maximizes his expected utility over time, given the farmer's resource constraints. In Texas County, where animal manure is abundant and water is scarce, it is logical to assume that effluent collected from CAFOs should be used as a source of water and nutrients for crops. However, using animal effluent must conform to strict environmental regulations, and using aquifer water in conjunction with 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.

As described in Carreira, we assume that the crop producer maximizes his expected utility of a stream of net returns (π_t) and the wealth of the farm in terms of the value of the water in the aquifer (Ω_t, note that this wealth declines over time if irrigation occurs), given the constraints faced by the producer and the underlying probability distributions as described here, by choosing the optimal irrigation system (SDI or CPS, designated by H) and the optimal decision path (Δ_d), as in

$$(1) \qquad \max_{H,\Delta_d} E\left[\frac{U_t(\pi_t + \Omega_t)}{(1+r)^t}\right];$$

the decision path is defined as the level of effluent and irrigation to apply over time, as in

the definition of π_t. A power utility function is assumed and defined as

$$(2) \qquad U_t(\pi_t + \Omega) = \frac{(\pi_t + \Omega_t)^{1-\psi}}{1 - \psi},$$

where ψ refers to the coefficient of relative risk aversion. In the power function the Arrow–Pratt absolute risk aversion coefficient is $\psi/(\pi_t + \Omega_t)$, computed by taking the negative of the ratio of the second derivative of the utility function to the first derivative of the utility function with respect to total wealth. The relative risk aversion coefficient is given by the parameter ψ. This utility function exhibits the following desirable properties: decreasing absolute risk aversion and constant relative risk aversion (Gray et al.).

Risk can refer to many things, but in the present context is defined 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, or application of fertilizer, which they believe will (and most of the time it 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 defined to be the agent's expected utility function, which is assumed to be a transformation of the producer's net revenue function. 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.

The basic form of the net returns at any year is given by

$$(3) \qquad \pi_t = \theta[P^c E(Y_t) - C^e F_t - (C^m - C^W W_t)G_t - OVC] - C^{IS}[r/1 + (1 + r)^{-\bar{Q}}] + (1 - \theta)R^w,$$

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 groundwater used in irrigation, W_t is the quantity of water in aquifer, C^W is the unit value of the water extracted, and C^m represents the cost of extracting the next-to-last unit of water extracted. As the volume of water in the aquifer (W_t) declines, the water must be pumped from farther down the aquifer, reducing $C^w W_t$, which then increases the extraction cost $(C^m - C^w W_t)$ per unit of groundwater used in irrigation. OVC represents other operating variable costs related to pesticide, corn seed, crop insurance, machinery fuel, lube, repairs, and operating capital. 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 irrigated corn in year t (for the first year, if we use a center pivot, $\theta = .7875$; for the SDI, $\theta = 0.9688$). 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 labile phosphorus in effluent. Other nutrients such as potassium are not considered. The functional form for yield is modeled as a modified Mitscherlich-Baule function, thus

$$(4) \qquad Y_t = (\eta_{01} + \eta_{02}D) \times [1 - \exp(\eta_{11}SN_t + \eta_{12}N_t + \eta_{13}V_t)] \times [1 - \exp(\eta_{21}SP_t + \eta_{22}P_t)] \times [1 - \exp(\eta_3 G_t)] + \varepsilon_t,$$

where $\eta_{01}, \ldots, \eta_3$ are the parameters to be estimated. The parameters corresponding to input application (η_{11}, η_{12}, η_{21}, η_{22}, η_3) are assumed to be negative and the parameter corresponding to ammonia loss (η_{13}) 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 CPS—this

parameter is expected to be negative, implying that the potential yield for SDI is greater than the potential yield for CPS. V_t is the expected level of ammonia volatilization 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 labile phosphorus. ε_t is a heteroskedastic random error term distributed as $\varepsilon_t \sim N(0, \exp(\alpha_0 + \alpha_1 G_t))$, which when $\alpha_1 < 0$ implies that variance of yield declines as the irrigation level increases. This functional form assumes that if there is no irrigation, irrigated corn yield is zero. Such an assumption is realistic for the area, as under a semiarid climate with inadequate rainfall a crop of irrigated corn could require as much as 30 acre-inches of irrigation.

The nitrogen carryover equation is defined as

$$(5) \quad SN_{t+1} = \lambda_0 + \lambda_1 SN_t + \lambda_2 N_t + \lambda_3 Y_t + \lambda_4 K_t + \lambda_5 V_t + \vartheta_t,$$

where K_t represents deep nitrogen percolation, which is very relevant in SDI but is negligible for CPS; thus it is expected that $\lambda_4 = 0$ for CPS but $\lambda_4 < 0$ for SDI. The parameters are not the same for both systems, but the underlying hypotheses are $\lambda_3 < 0$ and $\lambda_5 < 0$ while $\lambda_1 > 0$ and $\lambda_2 > 0$. The underlying distribution of the error term is $\vartheta_t \sim N(0, \exp(\phi_0 + \phi_1 G_t + \phi_2 N_t))$. The variance of the error term is assumed to increase with the irrigation level, thus $\phi_1 > 0$.

The level of labile phosphorus available to the plant is a combination of soil phosphorus and phosphorus in effluent applied. The phosphorus carryover equation refers to labile phosphorus (i.e., phosphorus that is available for plant use). 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 (Sharpley et al.). The phosphorus carryover constraint is defined as

$$(6) \quad SP_{t+1} = \delta_0 + \delta_1 SP_t + \delta_2 P_t + \delta_3 Y_t + \varpi_t,$$

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

Since the application of nitrogen with a CPS 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 was not estimated for the CPS. In the case of SDI, deep nitrogen percolation is of concern, and this function is defined as

$$(7) \quad K_{t+1} = \exp(\gamma_0 + \gamma_1 SN_t + \gamma_2 N_t + \gamma_3 Y_t + \gamma_4 G_t N_t + \gamma_5 G_t SN_t + \xi_t).$$

The error term is distributed as $\xi_t \sim N(0, \exp(\varphi_0 + \varphi_1 G_t))$ and it is expected that $\gamma_1, \gamma_2 > 0$, while $\gamma_3 < 0$; 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. The decline in the water table is assumed to be due to irrigation only and there is no recharge of the aquifer. The remaining water supply is defined as

$$(8) \quad W_{t+1} = W_t - G_t.$$

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 a random variable that follows a probability distribution based on the work of Taylor (see appendix for proof of PDF) using trigonometric transformations and defined as

$$(9) \quad f(V|N, U) = 0.5(\rho_1 - \rho_2 V^{-2} \times \cosh^{-2}(\rho_0 + \rho_1 V + \rho_2 V^{-1} + \rho_3 N),$$

which satisfies the conditions for a PDF if $\rho_1 > 0$ and $\rho_2 > 0$. When using hyperbolic trigonometric transformations, it is necessary to impose parameter restrictions to ensure that

the estimated function qualifies as a probability density function (Moffit).

Data and Empirical Work

For the period 2002–2003 in Texas County, the median value of soil test P index was 74 and the median value of soil pH was 7.8 (Zhang and McCray). Almost all of Texas County overlies the Ogallala Aquifer. It was assumed the area to be irrigated was a quarter section of land with the characteristics of an average Texas County 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 375 feet, the aquifer saturated area was 120 feet deep, porosity was about 50%, and aquifer specific yield was 15%. These assumptions were defined after consulting with a plant and soil scientist (Hattey) and a biosystems and agricultural engineer (Kizer) familiar with farming operations in Texas County, OK.

It was assumed that the farm's well is located near the center of one side of the field and that its capacity is 1000 gpm. As noted, the farm is assumed to produce irrigated corn and dry land wheat when CPS is used; SDI enables corn irrigation of the entire field with the exception of five acres lost to turn rows. The initial water supply is assumed to be constant for the field. However, there is less water available per acre irrigated with the SDI system. For the context of this study, irrigation uses a mixture of swine effluent and fresh groundwater. Based on previous Kansas State University publications, the cost of the CPS per irrigated acre was approximately $383 updated from the 2001 estimate at an annual rate of 3% (Dumler and Rogers). The cost of the SDI system was estimated to be about $708 per irrigated acre. Both irrigation systems are assumed to have a 15-year life.

Because experimental data were not available, the empirical implementation relies on biophysical data generated in EPIC (Erosion Productivity-Impact Calculator). EPIC input consisted of weather data, geographical and geological characteristics of the region (soil test results, type of soil, slope, etc.), management choices (effluent and irrigation applied), and type of crop (irrigated corn or dry land wheat). After data were simulated, several econometric relationships were estimated (for soil nitrogen carryover, soil phosphorus carryover, nitrogen percolation, and irrigated corn yield). Yield response to effluent nutrients and irrigation was estimated with SAS procedure NLMIXED. Carryover equations were estimated using procedure AUTOREG in SAS, designed for estimation of functions linear in the parameters and error term but with flexible variance-covariance structures. A probability density distribution for ammonia volatilization was also estimated using SAS procedure NLMIXED. From the EPIC yield simulations, it was estimated that on average for the CPS, 24% of the nitrogen applied volatilizes as ammonia, while the SDI has an 8% volatilization rate. The percentage of ammonia volatilization is related to the amount of nitrogen applied and weather conditions. Thus it is of interest to introduce ammonia volatilization as a source of risk in the stochastic model. The baseline optimization of producer's expected utility used the estimated econometric functions and a real discount rate of 5%. The production horizon considered was 100 years, which is enough time for aquifer depletion to take place or become imminent, given irrigation. The sensitivity analysis of the baseline solution used the following scenarios: (i) a drop in initial aquifer level of 50%, (ii) an increase in the real discount rate from 5% to 10%, and (iii) an increase in the price of natural gas from $3.50 to $5 per thousand cubic feet. The stochastic optimization model was implemented using a Visual Basic routine called the Large-Scale GRG Solver (it is a generalized reduced gradient solver capable of solving large smooth nonlinear problems) developed by Frontline Systems, Inc.

Results

Results pertaining to the choice variables are presented in Table 1. Given the assumed parameter values and estimated functions, corn irrigation would be feasible for about 85 years

Table 1. Decision Variable Summary and Sensitivity Analysis Results for Stochastic Dynamic Optimization Model

		Irrigation System and Scenario							
		Subsurface Drip Irrigation				Center-Pivot Sprinkler Irrigation			
Variables	Unit	Original	½ W_{Sup}	r = 10%	P_{NG} = \$5	Original	½ W_{Sup}	r = 10%	P_{NG} = \$5
Irrigation level									
Irrigation life	Years	85	44	84	88	100	54	100	90
Annual average/irrigated area	Ac-inch	7.68	7.42	7.78	6.99	7.71	7.36	7.76	7.07
Lifetime application to irrigated field	Ft	8,425	4,216	8,438	7,953	8,097	4,177	8,153	6,690
Effluent applied (N and P)									
Annual average/irrigated area	lb/a	237	236	239	233	266	257	261	257
Lifetime application to irrigated field	Ton	1,565	804	1,555	1,586	1,676	875	1,647	1,457

Notes: The scenarios are (i) original scenario; (ii) reduction of initial water supply/aquifer level by 50%; (iii) increase in real discount rate from 5% to 10%; and (iv) increase in cost of natural gas from \$3.50 to \$5 per 1,000 cubic feet. Unless otherwise noted, averages over area refer to averages taken over irrigated area (155 acres for SDI and 126 acres 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 the aquifer becomes economically depleted; dry land is cultivated with wheat. Expected Net Revenue refers to revenues of irrigated (cultivated with corn) and nonirrigated (cultivated with wheat) land. Because EPIC uses metric units and because of conversion and rounding errors, small discrepancies may be possible between averages and total values.

with SDI and at least 100 years with CPS. The difference between the average optimal irrigation levels for each system is small—the SDI uses on average 0.079 inches or less annually. If one is concerned with aquifer life, SDI could potentially deplete the aquifer at a faster rate than the CPS if the irrigated area under SDI is greater than with CPS. But, in terms of optimal level of effluent applied, more effluent nutrients are applied with the CPS on average annually, which is a logical result as ammonia volatilization is more likely to occur under this system. We assumed that the effluent nutrients were 78% nitrogen (N) and 22% labile phosphorus (P). Thus, in the SDI baseline solution, this corresponds to an annual average of 184.9 lbs/acre of N and 52.14 lbs/acre of P; in the CPS baseline solution, the annual average application of N is 207.5 lbs/acre and 58.5 lbs/acre of phosphorus (extension recommendations for nutrient application to irrigated corn are 207.5 lbs/acre of N and 80.5 lbs/acre of P). The average manure nutrient application rates estimated by Ribaudo et al. for Oklahoma using the 1998 ARMS hog survey data were 92.2 lbs/acre of N and 32.6 lbs/acre of P, thus applying effluent to irrigated corn could reduce the need for spreading land compared to other less nutrient-intensive crops. In cumulative terms, more water is used to irrigate the quarter section under SDI than under CPS because with SDI 155 acres are irrigated and with CPS 126 acres are irrigated (with the remaining land being in a dry land wheat-fallow rotation).

A summary of the endogenous variables' results is presented in Table 2. For this study, soil nutrients were tracked during the irrigation period and over the irrigated area. Nitrogen removal is close to the nitrogen application rate, confirming that soil nitrogen accumulation is not likely to be a problem. The optimization used an initial soil nitrogen level of 18 lb/a. At the end of the irrigation production horizon (85 years for the SDI and 100 years for the CPS), the soil nitrogen level predicted by the model was 17 lb/a for the SDI and 19 lb/a for the CPS, so there is not much difference between the two irrigation systems in terms of potential accumulation. This is not the case for the level of soil phosphorus. The starting point for soil phosphorus was 27 lb/a; in year 85, the soil phosphorus level predicted for SDI was 119 lb/a. However, in year 100 the level of soil phosphorus predicted for the CPS was 158 lb/a. On average, the soil phosphorus level for the SDI was 79 lb/a, and for the CPS irrigation it was 102 lb/a. These results should be considered estimates. It is rather difficult to predict nutrient accumulation over such long periods and the equations for soil nutrient accumulation are rather rudimentary. Nevertheless, the trends identified in these results are consistent with the best understanding of soil chemistry at this time. Soil phosphorus accumulation is more likely with CPS irrigation because more effluent is applied (Table 1) and corn yield is lower (Table 2), thus application is higher and removal is lower than with the SDI. In regions where soil phosphorus accumulation may be of concern, it is preferable to use SDI than CPS irrigation when applying swine effluent.

We computed the net present value[1] (NPV)

[1] Because of the unequal irrigation lifetimes, there may be some confusion on whether the equivalent annuity approach should be used instead of the NPV approach. This is a valid concern when one looks at choosing between mutually exclusive investments when at least one of them is replaceable (Bierman and Smidt; Levary and Seitz). The issue of replacement is very important because it could be that one project has a lower lifetime and lower cash flow than another. If there is not the possibility of replacement, then one prefers the project with the higher cash flow. If one of the projects can be replaced then one would need to either look at the NPV of each investment for a sequence of projects such that the length of the sequence is the same for both investments (for example if project A lasts two years and project B lasts three years one would look at the NPV of a sequence of three projects A versus the NPV of a sequence of two projects B, such that the total lifetime of each investment type would be six years) or one could compute the equivalent annuity which would set both cash flows in comparable terms; these are in fact equivalent procedures (Levary and Seitz). For the purpose of our analysis, the NPV is the correct comparison tool because although we have unequal irrigation lifetimes, the obvious reason is that these are due to the economical depletion of the aquifer, at which point the replacement of the irrigation system becomes an irrelevant issue (see Levary and Seitz's enlightening discussion of the equivalent annuity procedure).

Table 2. Endogenous Variable Summary and Sensitivity Analysis Results for Stochastic Dynamic Optimization Model

		Irrigation System and Scenario							
		Subsurface Drip Irrigation				Center-Pivot Sprinkler Irrigation			
Variables	Unit	Original	½ W_{Sup}	r = 10%	P_{NG} = \$5	Original	½ W_{Sup}	r = 10%	P_{NG} = \$5
Soil nitrogen									
Average over time and area	lb/a	17	18	16	18	19	19	15	19
Soil phosphorus									
Average over time and area	lb/a	79	56	78	79	102	71	99	93
Corn yield									
Annual average/irrigated area	Tn/a	5.44	5.40	5.49	5.35	5.17	5.13	5.13	5.04
Lifetime corn production of irrigated field	Ton	58,126	29,902	57,639	58,916	52,799	28,144	52,506	46,466
Net present value									
Lifetime expected net revenue (farm)	\$	512,026	446,367	264,581	437,812	474,448	424,778	240,321	413,933
Certainty equivalent of net revenue (farm)	\$	511,702	445,990	264,427	437,474	474,122	424,406	240,165	413,598

Notes: The scenarios are (i) original scenario; (ii) reduction of initial water supply/aquifer level by 50%; (iii) increase in real discount rate from 5% to 10%; and (iv) increase in cost of natural gas from \$3.50 to \$5 per 1,000 cubic feet. Unless otherwise noted, averages over area refer to averages taken over irrigated area (155 acres for SDI and 126 acres 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 the aquifer becomes economically depleted; dry land is cultivated with wheat. Expected Net Revenue refers to revenues of irrigated (cultivated with corn) and nonirrigated (cultivated with wheat) land. Because EPIC uses metric units and because of conversion and rounding errors, small discrepancies may be possible between averages and total values.

for the production horizon for each system, taking into account the cash flow for the period when there was irrigation and the period when irrigation was economically infeasible and dry land wheat was cultivated instead. The NPV of the lifetime (100 years) expected net returns for the farm is higher for the SDI ($512,026) than for the CPS ($474,448), which is due mainly to two factors: (i) corn yield is slightly higher with the SDI than with the CPS and (ii) a greater portion of the farm is irrigated with the SDI than with the CPS. Over time, these additional benefits compensate for the greater initial cost of the SDI. The attentive reader will notice that under two scenarios (baseline and using a 10% discount rate) the CPS did not deplete the aquifer in the 100-year production horizon. In both cases, the remaining water supply allows for an additional three years of irrigation; however, since this occurs so far into the future (years 101–103), its impact on the NPV is small enough that it does not overturn the advantage of the SDI over the CPS.

The certainty equivalent is the amount of money an agent (in this case the farmer) is willing to receive to not participate in the risky activity. For a risk-averse individual, it is lower than the expected net income as the person is willing to forfeit part of the income to reduce their exposure to risk; this difference is referred to as the risk premium. There is not much difference between the two systems' risk premiums ($324 for the SDI and $326 for the CPS) but the certainty equivalent is higher for the CPS as irrigation with this system has more risk in terms of ammonia volatilization and yield variability.

Based on the results from the baseline solution, SDI is preferred to CPS. The difference between the two systems is not great but it is invariant to the three alternative scenarios considered in the sensitivity analysis (see Tables 1 and 2).

Conclusions and Discussion

The overall conclusions of the study indicate that given the assumptions, SDI is preferred to CPS when using a mix of aquifer water and swine effluent to irrigate corn. If resources are used efficiently, SDI conserves more nitrogen and water than CPS and thus less swine effluent is applied, which limits the amount of effluent that CAFOs can land apply over time. On the other hand, because phosphorus accumulation and nitrogen volatilization are less likely with the SDI, CAFOs' potential adverse effect on the surrounding environment also will be less likely.

Although SDI is a more costly system, our results indicate that it does provide farmers with greater benefits in terms of greater irrigation savings, precision, nitrogen conservation, lower phosphorus accumulation, and higher expected crop yields. When one considers these benefits over long periods of time, they translate into revenues that outweigh the additional initial investment cost of the SDI. This conclusion did not change with any of the sensitivity analysis considered. Given the 100-year production horizon, the estimated difference in net present value between the two systems of $37,578 is not large and some producers may be unwilling to change their irrigation system based on such a difference.

Presently, farmers can receive a monetary incentive from the Environmental Quality Incentives Program (EQIP) to adopt water-efficient irrigation systems. The EQIP funds can be used by farmers to outweigh part of the costs of implementing an SDI system. As introduced in the 1996 FAIR Act (also known as the Freedom to Farm 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 (USDA–ERS). In 2002, EQIP reimbursed up to 50% 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). The intent of the EQIP subsidy tends toward adoption of more water-efficient irrigation systems, but does this mean that aquifer life will be extended? Our results indicate that merely adopting more water-conserving technology such as SDI does not extend aquifer life; to lengthen aquifer life, irrigated acreage under SDI must also be reduced. Thus, subsidizing SDI with the aim of extending aquifer life could be counterproductive unless the funds are allocated with the additional condition that part of the land must revert to dry land. A close look at the 2002 Census of Agriculture reveals that in Texas County there was a 28% increase in the irrigated acreage under corn for grain between 1997 and 2002, which could shorten aquifer life in the region.

Because SDI is a relatively new technology, this study should be repeated at a later time when actual experimental data are available. Further data should also be collected regarding the long-term management issues of SDI and system lifetime.

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Appendix

Mathematical Proof of Ammonia Volatilization PDF

Following Taylor's work, one can use a hyperbolic tangent function to estimate a probability distribution function with a closed form CDF. This PDF has a bell shape, but it is not necessarily symmetric. Since ammonia volatilization (V) is a physical measure, $0 \leq V < +\infty$. We know that given a variable x, such that $-\infty < x < +\infty$, then the hyperbolic tangent of x is defined as

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

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

$$(11) \quad 0 \leq 0.5 + 0.5 \tanh(x) \leq 1.$$

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

$$(12) \quad 0 \leq 0.5 \cosh^{-2}(x) \leq 1.$$

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

$$(13) \quad 0 \leq 0.5 + 0.5 \tanh[\Psi(V)] \leq 1.$$

A suitable transformation of ammonia volatilization is

$$(14) \quad \Psi(V|N) = \rho_0 + \rho_1 V + \rho_2 V^{-1} + \rho_3 N,$$

which allows Equation (14) to satisfy the conditions for a PDF if $\rho_1 > 0$ and $\rho_2 < 0$. Note that when the absolute values of ρ_1 and ρ_2 are different, the dis-

tribution of V is not symmetric. Given the ammonia volatilization CDF described in Equations (13) and (14), the PDF of ammonia volatilization is defined as

$$(15)\quad f(V|N) = \frac{d}{dV}[0.5 + 0.5\tanh(\rho_0 + \rho_1 V + \rho_2 V^{-1} + \rho_3 N)],$$

which yields

$$(16)\quad f(V|N) = 0.5(\rho_1 - \rho_2 V^{-2}) \times \cosh^{-2}(\rho_0 + \rho_1 V + \rho_2 V^{-1} + \rho_3 N).$$

Since $f(V|N) \geq 0$, $\forall V \in \mathbb{R}_0^+$ and $\int_0^\infty f(V|N)\,dV = 1$, equation (16) is a PDF.