Management Strategies to Mitigate Environmental Impact of Weather Uncertainty in Effluent Application to Irrigated Corn in Semiarid Regions

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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. Most of the equations estimated econometrically had heteroskedasticity problems and MLE was used. The econometric estimation of a PDF of ammonia volatilization dependent on amount of nitrogen applied, for each irrigation system, was successful and is the basis for developing a stochastic chain for the soil nitrogen carryover equation. The results of the stochastic dynamic programming model are still being developed and will be presented at the conference.

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Introduction

Following the expansion of the swine industry in Oklahoma during the 1990s, population concerns grew over the management of swine effluent and the environmental issues surrounding its application to crops (Branstetter). Animal production started out as a new hope for an economic debilitated Oklahoma Panhandle. Policy makers worked hard to provide the right incentives for this industry to locate in Oklahoma. As animal production began to thrive, environmental concerns and population discontentment pressured policy makers to take action against the same industry they had once worked so hard to nourish. The situation 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 (Hinton).

Most of the Oklahoma swine industry is located in the Panhandle, a semiarid region greatly dependent on the Ogallala aquifer for water (USDA). 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). Economic exhaustion will be achieved when "net returns per acre from dryland farming exceed net returns per acre from irrigation" (Harris, Mapp, and Stone). Current irrigation methods practiced in the county include furrow irrigation and sprinkler irrigation via a center pivot, none of which are very water conserving or nitrogen efficient (O'Brien, Dumler, and Rogers).

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, 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.

The objective of this study is to incorporate weather uncertainty in the producer's decision making process for farming in semiarid regions, thus developing long term best management practices for animal waste use and groundwater water use that are economically viable for the producer and maximize the returns of using the limited resources of the aquifer. The development of subsurface drip irrigation (SDI) in the 1960s, in Israel, allowed farmers to reap potential larger benefits from smaller and more precise applications of irrigation and effluent, by increasing water efficiency and reducing ammonia volatilization (Phene and Phene). However, the large amount of capital necessary to implement this technology and manage it has delayed its adoption. For this study, a subsurface drip irrigation system was budgeted at \$107,458 per irrigated quarter-section (\$693 per irrigated acre, see Table 1); while the costs of a center pivot system were estimated at \$48,243 for 126 acres (\$383 per irrigated acre, see Table 2). The inevitable economic depletion of the Ogallala Aquifer reserves in Texas County coupled with the need to manage effluent nutrient better, increases the attractiveness of this technology to farmers. The adoption of SDI in the Oklahoma Panhandle is a polarizing issue, as farmers struggle to stay in business with declining agricultural prices and more stringent environmental regulation.

Data and Study Implementation

Weather data for Texas County referring to the 1948-2002 period was used to compute relevant statistics to recreate the monthly statistical distributions of variables such as average precipitation, evaporation, solar radiation, minimum and maximum temperatures, average number of rain days, and the conditional probabilities of wet days and dry days. Using these distributions, different weather patterns were generated and input into EPIC where yield data were simulated for 25-year periods following an experimental design of effluent application, urea application and irrigation. The simulated data were used to estimate econometric equations for yield, nitrogen carryover in soil, nitrogen percolation, and phosphorus carryover in soil. The yield function is assumed to be nonlinear, with a Mitscherlich-Baule-type functional form. The Mitscherlich-Baule (M-B) production function offers nice properties such as a positive interaction between production factors, partial substitution among production factors, and a sigmoid production curve (Nijland and Schouls). 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. Beattie and Taylor is another valuable reference for production theory and production functional forms.

The probability distribution of ammonia volatilization is a key factor in the nitrogen carryover equation. Using previous work by Taylor, a probability distribution function for this variable was developed based on a hyperbolic cosine function. This function has the advantage of having a closed-form CDF. The probability distribution was defined such that the probabilities change according to the levels of effluent nitrogen and urea applied. The carryover equations for phosphorus and nitrogen were estimated using maximum likelihood taking into account multiplicative heteroskedasticity due to irrigation and level of nutrient applied.

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 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, Kemeny and Snell).

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

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

for each irrigation system. In equation (1) 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, C^U is the unit cost of urea, U_t is amount of urea 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, C^m represents maximum unit cost of pumping aquifer. Note that pumping costs are set up such 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 herbicide, gas, etc. 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, $\theta_1 = .7875$; for the SDI, $\theta_1 = 1$). The choice variables are quantity of water used in irrigation, quantity of effluent applied, quantity of urea applied, and proportion of land being irrigated.

Effluent nitrogen and effluent phosphorus are defined as $N_t = \sigma_N F_t$ and $P_t = \sigma_P F_t$, respectively, 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 interest 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

$$\begin{gathered} Y_t = \eta_0 \left\{1-\exp\left(\eta_{11} SN_t + \eta_{12} N_t + \eta_{13} U_t + \eta_{14} V_t\right)\right\}\left\{1-\exp\left(\eta_{21} SP_t + \eta_{22} P_t\right)\right\} \\ \left\{1-\exp\left(\eta_3 G_t\right)\right\} + \varepsilon_t \end{gathered}, \qquad (2)$$

where $\eta_0, \ldots, \eta_3$ 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 with respect to inputs. 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 change in the amount of nitrogen carryover equation is defined as

$$SN_{t+1} = \lambda_0 + \lambda_1 SN_t + \lambda_2 N_t + \lambda_3 U_t + \lambda_4 Y_t + \lambda_5 K_t + \lambda_6 V_t + \vartheta_t, \tag{3}$$

where K_t represents deep nitrogen percolation, which is very relevant in SDI but is negligible for sprinkler irrigation, thus we hypothesize that $\lambda_5 = 0$ for this system. The parameters are not the same for both systems but the underlying hypotheses for the parameter signs under both systems are $\lambda_1, ..., \lambda_3 > 0$ while $\lambda_4, ..., \lambda_6 < 0$. 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 effluent phosphorus applied. 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

$$SP_{t+1} = \delta_0 + \delta_1 SP_t + \delta_2 P_t + \delta_3 Y_t + \varpi_t, \tag{4}$$

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

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; in the case of SDI, deep nitrogen percolation is of concern since there is the risk that nitrogen might seep and contaminate the underground water table. .The nitrogen percolation function is defined as

$$K_{t+1} = \exp\left(\gamma_0 + \gamma_1 SN_t + \gamma_2 N_t + \gamma_3 U_t + \gamma_4 G_t + \xi_t\right). \tag{5}$$

The error term is distributed normal as $\xi_t \sim N\left(0, \exp\left(\varphi_0 + \varphi_1 G_t + \varphi_2 N_t\right)\right)$ and it is expected that $\gamma_1 > 0$, $\gamma_2 > 0$, $\gamma_4 > 0$ while $\gamma_3 < 0$. The source of variance is irrigation and effluent nitrogen level but it is possible that for the center pivot, the error term is homoskedastic. 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

$$W_{t+1} = W_t - G_t. \tag{6}$$

The first stage of this study consisted of estimating the econometric functions in SAS. The yield equation was estimated with procedure NLMIXED. The carryover equations and the nitrogen percolation equation 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.

The main assumption for the stochastic dynamic part of the study is that, although nitrogen application to the soil is a known quantity, the level of nitrogen that actually is available to the plant is unknown because part of the nitrogen is volatilized as ammonia, which is random because of weather conditions, amount applied, etc. Ammonia 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.)

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

$$\tanh\left(x\right) = \frac{e^{2x} - 1}{e^{2x} + 1} \tag{7}$$

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

$$0 \le 0.5 + 0.5\tanh\left(x\right) \le 1 . \tag{8}$$

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

$$0 \le 0.5 + 0.5\tanh\left[\Psi\left(V\right)\right] \le 1 . \tag{9}$$

A suitable transformation of the ammonia volatilization variable is

$$\Psi\left(V \middle| N, U\right) = \rho_0 + \rho_1 V + \rho_2 V^{-1} + \rho_3 N + \rho_4 U , \tag{10}$$

which, as can be seen below, can be used to derive a function that satisfies the conditions for a PDF, if $\rho_1 > 0$ and $\rho_2 < 0$. The magnitude of the parameters for volatilization (*V*), effluent nitrogen (*N*) and urea (*U*) variables allow the PDF to be nonsymmetrical-bell-shaped, as well as kurtotic. Thus, the PDF of ammonia volatilization is given by the derivative of equation (9) with respect to *V,* which is

$$f\left(V\middle|N,U\right)=0.5\left(\rho_1-\rho_2V^{-2}\right)\cosh^{-2}\left(\rho_0+\rho_1V+\rho_2V^{-1}+\rho_3N+\rho_4U\right). \qquad (11)$$

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.

An algorithm was developed using Visual Basic for Applications in Microsoft Excel to implement the stochastic dynamic optimization for each irrigation system, such that the optimal path in terms of effluent and urea application as well as irrigation was identified, while taking into account the consequences of such decisions in terms of nutrient accumulation in the soil and aquifer life. The algorithm evaluates 550 possible state combinations for each year (11 aquifer states, 10 soil nitrogen states, 5 soil phosphorus states). Comparing the results for each system allows producers as well as policy makers to exercise an informed decision regarding the merits of each system in terms of monetary and environmental issues in the long run.

Results

Initially, the regressions for yield and nutrient carryover were to be estimated as a system of equations. Unfortunately, due to the nonlinearity of the yield equation, it was not possible to obtain convergence in the estimation with procedure NLMIXED in SAS, thus each equation had to be estimated separately. The parameter estimates for the heteroskedastic yield function are reported in Table 3. Since the function is nonlinear in the parameters, the parameters estimators are not normal, thus statistical tests are only asymptotically valid. For SDI, all parameters have expected signs and are significant at the 5 percent significance level with the exception of the soil phosphorus parameter estimate, which is positive and we had hypothesized it to be negative. However, the estimate is not statistically significant and the confidence interval for this estimate does contain negative values, thus we cannot reject the hypothesis that its true value is negative.

For center pivot sprinkler irrigation, all parameter estimates have expected signs, although the parameter estimates for effluent nitrogen and soil phosphorus are not statistically significant. The remaining estimates are all significant at the 10 percent significance level and some at the 5 percent significance level. The magnitude of the parameters indicates that irrigation is the critical input for corn yield, since it has the highest marginal effect *ceteris paribus* (note that the marginal effects with respect to an input variable for the M-B yield function is not equal to the variable parameter as is the case with a linear regression; however, the magnitude of the marginal effect is closely related to the magnitude of the parameter). As with SDI and as expected, the variance of yield declines as the level of irrigation increases.

Table 4 reports the parameters estimates for the carryover function for soil nitrogen. For SDI, soil nitrogen is heteroskedastic with the level of irrigation but not with effluent nitrogen (increasing irrigation, increases the variance of soil nitrogen); for center pivot, soil nitrogen is heteroskedastic with irrigation level and effluent nitrogen level. All the parameter estimates are statistically significant and have expected signs, except for nitrogen percolation for the center pivot, which as expected, is not statistically significant. The R-Square for both models was extremely high (above 0.99), which is predictable as we are using simulated data.

The regression results for the soil phosphorus carryover equation are reported in table 5. The R-Square for the SDI regression is 0.65. There are several possible reasons to explain this low R-square. Firstly, it may indicate that we should look at the level of soluble soil phosphorus at different soil depths and not just one single depth. Another pertinent issue is that as one applies phosphorus, part of it may enter less soluble phosphorus pools in the soil, thus although more phosphorus exists in the soil, the amount of soil soluble phosphorus actually declines. If this is the case, then the soil phosphorus equation as described above is misspecified. The parameter estimates for the lag of soil phosphorus and effluent phosphorus have expected signs, but we expected higher magnitudes. The parameter estimate of yield is positive and statistically significant; we expected it to be negative. For center pivot irrigation, all estimates have expected signs and are statistically significant. For both irrigation systems, the error term for this regression exhibits multiplicative heteroskedasticity due to irrigation and level of effluent phosphorus applied, as expected.

The parameter estimates for the nitrogen percolation equation are reported in Table 6. All parameter estimates have expected signs for both systems and are statistically significant. The R-Squares for both regressions are around 0.65, which we expected to be higher. At the 5 percent significance level, the error term for the center pivot regression was homoskedastic, thus ordinary least squares were used to estimate this regression. The error term for the SDI had non-constant variance due to effluent nitrogen applied, so maximum likelihood estimation was used. The mobile nature of nitrogen in the soil profile may warrant the need to look into nitrogen percolation at different soil depths, which will likely improve the results of this regression for both irrigation systems.

Table 7 contains the parameter estimates for the probability distribution of ammonia volatilization. The parameter estimates have the necessary signs for the functions to be consistent with the requirements for a probability distribution function. All parameter estimates are statistically significant. For both systems, the PDFs are shorter and broader for lower levels of nitrogen applied. This confirms our expectations that for lower levels of nitrogen application, ammonia volatilization has a higher variance and the distribution has smaller kurtosis than for greater levels of nitrogen application.

The results of the stochastic dynamic optimization procedure are still underway and will be reported at a later time.

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 being developed. The algorithm developed to obtain the solution for the stochastic optimization is working but still needs to be refined. Although doable, the time used to produce a solution is lengthy—about 10 hours for a 100 year simulation on a personal computer with about 260 MB of RAM and a 1700 MHZ processor.

For the econometric estimations, as expected, our results show that homoskedasticity is unrealistic and the econometric estimation of the equations for yield and nutrient carryover should be done with maximum likelihood. The analysis can be improved once a system of simultaneous equations for the yield function and the carryover functions can be estimated for each irrigation system. The equations for soil phosphorus as estimated seem to be misspecified and a slightly more complex relationship should be introduced at a later time to refine the present relationships. The same is true for the nitrogen percolation equation. As experimental data becomes available, model validation should be implemented.

Appendix I: Tables

Table 1. Subsurface Drip Irrigation System Budget (2003)

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	hours	$375.00	2	$750.00
Labor for trenching	hours	$10.00	15.5	$155.00
Labor to install pipes	foot	$0.10	11880	$1,188.00
Other labor	hours	$10.00	984.5	$9,845.00
Total SDI Cost	$			$107,458.00
Total SDI Cost/acre	$/ac			$693.28
Total SDI Cost/ha	$/ha			$1,713.13

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

Notes:

1. Area: 160 acres; irrigated area: 155 acres.

Table 2. Center Pivot Irrigation System Budget

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
2003 updated cost (assuming 3% annual cost increase)	$/acre			$383.14
2003 updated cost	$/ha			$946.76

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

Note:

1. Area: 160 acres; irrigated area: 126 acres.
2. System lateral: 1,320 feet.

Table 3. Irrigated Corn Yield Function Parameter Estimates Computed With The Gauss-Newton Method In SAS Procedure NLMIXED

		Parameter Estimates	
Variable	Symbol	Subsurface Drip Irrigation	Center Pivot Sprinkler Irrigation
Pseudo-Intercept	η_0	13.2591*	13.1871*
		(0.0748)	(0.0849)
Soil Nitrogen	η_{11}	-0.04462*	-0.3108*
		(0.0240)	(0.0151)
Effluent Nitrogen	η_{12}	-0.04885*	-0.00033
		(0.0046)	(0.0016)
Urea	η_{13}	-0.06532*	-0.00253**
		(0.0055)	(0.0015)
Ammonia Volatilization	η_{14}	0.5643*	0.01141**
		(0.0555)	(0.0066)
Soil Phosphorus	η_{21}	0.0349	-0.01984
		(0.1025)	(0.0223)
Effluent Phosphorus	η_{22}	-0.4888*	-0.3007*
		(0.1309)	(0.0495)
Irrigation	η_3	-0.5252*	-0.4971*
		(0.0090)	(0.0087)
Variance Intercept	α_0	1.7363*	1.4907*
		(0.0582)	(0.0584)
Variance Slope (Irrigation)	α_1	-0.3265*	-0.2857*
		(0.0162)	(0.0163)

Notes: Values in parenthesis refer to approximate standard errors of parameter estimates. *Parameter estimate significant at 5 percent significance level. ** Parameter estimate significant at 10 percent significance level. *N*=3,780; AIC for SDI and center pivot were 13,242 and 12,822, respectively.

Table 4. Soil Nitrogen Equation Maximum Likelihood Parameter Estimates Computed in SAS Procedure AUTOREG

		Parameter Estimates	
Variable	Symbol	Subsurface Drip Irrigation	Center Pivot Sprinkler Irrigation
Intercept	λ_0	2.5644*	2.1447*
		(0.0708)	(0.0534)
Lag Soil Nitrogen	λ_1	0.9934*	0.9958*
		(0.0081)	(0.0007)
Effluent Nitrogen	λ_2	0.0592*	0.0502*
		(0.0025)	(0.0018)
Urea	λ_3	0.0669*	0.0478*
		(0.0031)	(0.0013)
Yield	λ_4	-0.8226*	-0.7549*
		(0.0080)	(0.0067)
Nitrogen Percolation	λ_5	-0.0452*	**
		(0.0029)	
Ammonia Volatilization	λ_6	0.2816*	0.0872*
		(0.0309)	(0.0075)
Variance Intercept	ϕ_0	0.7154*	0.5137*
		(0.0184)	(0.0171)
Variance Slope (Irrigation)	ϕ_1	0.1061*	0.0874*
		(0.0142)	(0.0126)
Variance Slope (Effluent Nitrogen)	ϕ_2	**	0.0047*
			(0.0003)

Notes: Values in parenthesis refer to standard errors of parameter estimates. *Parameter estimate significant at 5 percent significance level. **Parameter not significant statistically and omitted from model. *N*=3,780; R-Squares for SDI and center pivot were 0.9996 and 0.9994, respectively.

Table 5. Soil Phosphorus Equation Maximum Likelihood Parameter Estimates Computed in SAS Procedure AUTOREG

		Parameter Estimates	
Variable	Symbol	Subsurface Drip Irrigation	Center Pivot Sprinkler Irrigation
Intercept	δ_0	0.8982*	3.9411*
		(0.2409)	(0.3558)
Lag of Soil Phosphorus	δ_1	0.6205*	0.7272*
		(0.0085)	(0.0109)
Effluent Phosphorus	δ_2	0.0223*	0.9564*
		(0.0039)	(0.0376)
Yield	δ_3	0.1611*	-0.8529*
		(0.0200)	(0.0433)
Variance Intercept	κ_0	3.3158*	3.9450*
		(0.1072)	(0.1370)
Variance Slope	κ_1	-0.1087*	-0.2438*
(Irrigation)		(0.0142)	(0.0141)
Variance Slope	κ_2	0.0059*	0.0833*
(Effluent Phosphorus)		(0.0016)	(0.0018)

Notes: Values in parenthesis refer to standard errors of parameter estimates. *Parameter estimate significant at 5 percent significance level. *N*=3,780; R-Squares for SDI and center pivot were 0.6478 and 0.9504, respectively.

Table 6. Nitrogen Percolation Equation Parameter Estimates Computed in SAS Procedure AUTOREG (Dependent Variable: Log of Nitrogen Percolation)

Variable	Symbol	Parameter Estimates Subsurface Drip Irrigation (MLE)	Parameter Estimates Center Pivot Sprinkler Irrigation (OLS)
Intercept	γ_0	-8.7961*	-9.2994*
		(0.9782)	(1.1251)
Soil Nitrogen	γ_1	0.0606*	0.0904*
		(0.0191)	(0.0152)
Effluent Nitrogen	γ_2	0.0296*	0.0315*
		(0.0058)	(0.0043)
Urea	γ_3	0.0261*	0.0306*
		(0.0060)	(0.0051)
Yield	γ_4	-0.2424*	-0.4781*
		(0.0987)	(0.0965)
Irrigation	γ_5	0.7241*	0.9683*
		(0.1864)	(0.1999)
Variance Intercept	φ_0	2.4763*	**
		(0.2912)	
Variance Slope (Effluent Nitrogen)	φ_1	-0.0027* (0.0013)	**

Notes: Values in parenthesis refer to standard errors of parameter estimates. *Parameter estimate significant at 5 percent significance level. **Parameter not significant statistically and omitted from model. *N*=3,780; R-Squares for SDI and center pivot were 0.6442 and 0.6508, respectively.

Table 7. Ammonia Volatilization PDF Parameter Estimates Computed in SAS Procedure NLMIXED

		Parameter Estimates	
Variable	Symbol	Subsurface Drip Irrigation	Center Pivot Sprinkler Irrigation
Intercept	ρ_0	-0.4795* (0.1308)	0.7553* (0.1266)
Ammonia Volatilization	ρ_1	1.8935* (0.0270)	0.4618* (0.0068)
Inverse of Ammonia Volatilization	ρ_2	-3.2854* (0.6752)	-10.7084* (1.6423)
Effluent Nitrogen	ρ_3	-0.1541* (0.0022)	-0.1120* (0.0016)
Urea	ρ_4	-0.1902* (0.0027)	-0.0775* (0.0011)

Notes: Values in parenthesis refer to approximate standard errors of parameter estimates. *Parameter estimate significant at 5 percent significance level. *N*=3,780; AIC for SDI and center pivot were 5290.2 and 15,925, respectively.

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