THE MANURE RISK PREMIUM: THE ECONOMIC AND ENVIRON,ENTAL COST OF UNCERTAINTY & VARIABILITY IN MANURE NITROGEN SUPPLY

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ABSTRACT

Manure exhibits greater variability in nitrogen concentration, plant availability, and application uniformity than synthetic fertilizers. Because corn yield responds to nitrogen with diminishing marginal returns, nitrogen deficiency is more costly than moderate oversupply. Consequently, producers have an economic incentive to apply additional nitrogen to hedge against uncertainty, a phenomenon we define as the manure risk premium. We developed a stochastic Monte Carlo model incorporating variability in manure nitrogen concentration, application uniformity, ammonia volatilization, nitrogen availability, and application timing to quantify how uncertainty influences economically optimal nitrogen rates. Increasing uncertainty in nitrogen concentration, plant availability, and application uniformity systematically increased profit-maximizing nitrogen rates, even when expected manure nitrogen supply remained unchanged. Under realistic management scenarios, the manure risk premium increased optimal nitrogen rates by 10–73 kg N ha^{-1} and nitrogen losses by 4–46 kg N ha^{-1}, demonstrating that uncertainty carries both economic and environmental costs. Mote Carlo model results suggest that eliminating manure nutrient variability could reduce corn production costs by up to \$253 ha^{-1} in continuous corn and \$177 ha^{-1} in corn-soybean rotations while reducing modeled statewide nitrate losses by up to 8%. These findings demonstrate that uncertainty in manure nitrogen supply biases optimal nitrogen rates upward. Technologies that improve nutrient delivery predictability could reduce nitrogen losses without sacrificing yield. The manure risk premium provides a quantitative framework for evaluating manure management practices and precision technologies based on their economic and environmental benefits.

INTRODUCTION

Agricultural systems must increase production while minimizing environmental impacts as global population growth places increasing pressure on finite land resources (Foley et al., 2011; Islam, 2025). Key challenges include both the expansion of cropland into natural ecosystems and the inefficient use and loss of essential nutrients such as nitrogen (N) and phosphorus (P) (Tilman et al., 2001). Such losses contribute to greenhouse gas emissions, water quality degradation, and eutrophication (Liu et al., 2024; Sakadevan & Nguyen, 2017), increasing scrutiny of nutrient use efficiency across agricultural systems, particularly within animal agriculture (Steinfeld et al., 2006).

Nitrogen management is central to both profitable and environmentally responsible crop production (Govindasamy et al., 2023). In systems using commercial fertilizers, the relationship between applied N and crop yield is well characterized (Cassman et al., 2002), and applied rates closely match intended targets due to precise metering (H. M. Hanna et al., 2006), with generally consistent spatial distribution across application equipment (H. M. Hanna et al., 2002; M. D. Schrock et al., 2001; P. M. Boyd et al.,

2004). Unlike synthetic N fertilizers, for which the intended application rate and N concentration can be measured and controlled relatively precisely, manure N supply is uncertain at several points between application and crop uptake. Uncertainty arises from variation in manure N concentration and chemical forms, spatial variation in application rates & uniformity, and differences in the fraction of applied N that remains or becomes plant available following application and soil transformations (Aguirre-Villegas et al., 2018; D. L. Karlen et al., 2004; Dougherty et al., 2022; Funk et al., 2003; Regan & Andersen, 2014; Villanueva et al., 2024).

Manure recycling through land application closes nutrient loops, reduces dependence on synthetic fertilizers, and lowers production costs (Honeyman, 1996; Wang et al., 2026). However, realizing these benefits depends on accurate knowledge of manure nutrient content and plant availability (Sharpley et al., 1998/1998). In practice, manure nutrient applications are influenced by substantial uncertainty arising from variation in manure composition (i.e. nutrient concentration) and animal type across farms and years (ASABE, 2005; Barth, 1985; Payne, 1986; Rieck-Hinz et al., 1996). There is also a reliance on historical sampling or generalized, outdated reference values for many manure types, which makes application less accurate (Davis et al., 2002).

In addition, manure management practices such as storage can substantially influence N retention through ammonia volatilization and other loss pathways (Barth, 1985; Burton & Beauchamp, 1986; Genedy & Ogejo, 2023; Rieck-Hinz et al., 1996), thereby affecting both total N content and plant-available N (Calculating Manure Application Rates, 2007; Lory et al., 2007; Rayne & Larson, 2025). Likewise, application equipment, application method, and soil and weather conditions at the time of and following land application influence N conservation and transformation processes, including volatilization, nitrification, and nitrate leaching, while also contributing to variability in field-level nutrient distribution (Arora & Andersen, 2016; Dougherty et al., 2022; Norman-Ham et al., 2008; Sommer & Hutchings, 2001; Webb et al., 2010).

The economically optimal N rate is inherently uncertain because crop N demand cannot be known with certainty at the time of fertilizer application. Weather, soil N mineralization, yield potential, and N losses occurring throughout the growing season all influence the amount of N required to maximize profit. Consequently, producers must balance the expected return from additional N against the risk of under-supplying the crop. Manure adds a second source of uncertainty on the supply side because the amount of plant-available N delivered to the crop is itself uncertain. Thus, manure-based N management requires decisions under uncertainty regarding both crop N demand and fertilizer N supply.

Because crop yield response to N exhibits diminishing marginal returns, the economic penalty associated with N under-application is typically greater than the penalty associated with moderate over-application (Sawyer et al., 2006). When the amount of plant-available N supplied by manure is uncertain, producers may therefore apply additional N as a precaution against potential N deficiency. Such an adjustment represents a risk premium associated with uncertainty in manure N supply. In such

situations, there remains an economically optimal N rate (EONR); however, given the economic risk asymmetry and the impossibility of perfect information the profit maximizing N rate will be higher.

The concept of a risk premium, or a difference between a profit maximizing rate and the economic optimum rate, has been examined in other stochastic agronomic decision contexts, including those involving weather and soil variability (Rajsic et al., 2009). However, while agronomic research has long recognized the variability of manure nutrient content and application characteristics (Chadwick et al., 2000; Dou et al., 2001), the quantitative implications of this variability for N rate decisions under uncertainty remain poorly quantified. Farmers and advisors often respond to this uncertainty by applying “a little extra” manure to guard against potential N deficiency (Funk et al., 2003), but the magnitude of this adjustment, and its dependence on the degree and structure of manure variability, remains uncertain.

In this study, we distinguish between variability in manure N supply and uncertainty in the resulting N rate decision. Variability describes actual differences in manure N concentration, application rate, and plant availability, whereas uncertainty describes the producer's limited knowledge of the amount of plant-available N that will be delivered to the crop. Although variability contributes to uncertainty, improved measurement and management can reduce uncertainty without necessarily eliminating the underlying variability.

Therefore, in this study, we developed a probabilistic Monte Carlo model to evaluate how uncertainty in manure N supply influences the profit maximizing N application rate. Manure characteristics, including total N concentration, application uniformity, N volatilization, N availability, and application timing, are represented as stochastic variables, allowing quantification of how each contributes to variability in plant-available N supply and resulting yield and revenue outcomes.

The objectives of this study were to:

- quantify how manure uncertainty shifts the profit-maximizing N rate,
- identify which sources of uncertainty most strongly influence that shift,
- evaluate how improvements in manure management recommendations could reduce both economic losses and environmental N impacts.

MATERIALS AND METHODS

Model Overview

A stochastic Monte Carlo model was developed in Python to quantify how uncertainty in manure N supply influences the profit maximizing N rate relative to the economically optimal N application rates for corn (*Zea mays*, USDA Plants Database). The model represents manure N supply as the product of several stochastic processes, including manure nutrient concentration, application rate, application uniformity, ammonia volatilization, plant-available N, and seasonal timing. Together, these processes

determine the distribution of plant-available N delivered to the crop for a specified target application rate.

Crop rotation (corn following corn or corn following soybean [*Glycine max*, USDA Plants Database]), a type of manure (animal type and manure storage system), a season of application (fall, spring, or while the plant is growing), and the application method (injection, immediate incorporation, surface application) are inputs to the model to determine the distribution of plant-available N delivered to the crop. Using these inputs, the model selects a nitrogen response curve and manure nitrogen supply characteristics and variabilities. Then, for each of 40 target N application rates, the model generated 3,000 possible realizations of manure nutrient supply. Each realization was translated into crop yield, economic return, and nitrate leaching outcomes. Expected economic return was then calculated across all realizations to identify the profit-maximizing application rate under uncertainty. A process flow diagram for the steps taken and the flow of data is provided in Figure 1.

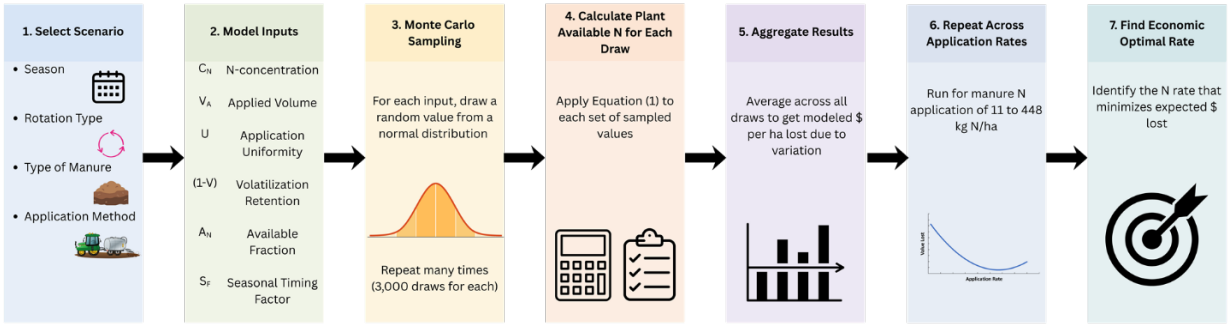


Figure 1. A process flow diagram indicating inputs and flow of data through our manure variability calculator. First, the type of manure, the application season, and the crop rotation are selected. Using these items, we provide the program with inputs that represent what was picked in step one. Each input is varied according to a normal distribution, and this is repeated 3000 times using Monte Carlo. For each repeat, the dollars lost are calculated and then averaged over all runs. This is repeated for each application rate of 11 kg N/ha to 448 kg N/ha. Using the spread of application rates, a trendline of loss vs. application rate is made to find the most economical rate for the inputs.

Model Inputs

Model input values were obtained from published literature (Tables 1–3). Mean values represented expected manure characteristics, while standard deviations represented uncertainty associated with each parameter. When literature reported only ranges, the mean was estimated as the midpoint of the range and the standard deviation as one-half of the reported range. All parameters were assumed to be normally distributed.

Table 1 summarizes manure N concentration on a wet (as-is) basis, first-year N availability, and application rate variability for each manure type. Table 2 summarizes N retention following application for different application methods (i.e., volatilization losses resulting from the application method chosen). Table 3 provides seasonal adjustment factors describing the difference in N supply among fall, spring, and sidedress applications. Both fall and sidedress are normalized to spring application. Spring was used as the standard because it represented the majority of trials used to generate the

crop nitrogen response curve in the maximum return to N (MRTN) trials, which were used as the basis for the crop response curve used in this work (Sawyer et al., 2006). The standard deviation reflects year-to-year variability, as reported in Willsea (2025).

Table 1. Manure characteristics for N supply for common Midwestern US manure systems, including N content, N availability, and consistency of application rate.

Manure Type	Manure N Content (kg N/Mg) Ave. (St. Dev.)	N Availability (% of Total N) Ave. (St. Dev.)	Application Volume (%) St. Dev.
Swine Finishing Deep Pit	7.00[a] (0.46[d])	95[h] (5[h])	100 (3.2[d])
Swine Finishing Lagoon	0.60[a] (0.18[e])	95[h] (5[h])	100 (3.2[d])
Swine Finishing Bedded Pack	4.50[c] (0.45[c])	40[i] (15[i])	100 (5.0[j])
Dairy Lagoon	0.73[a] (0.22[e])	50[i] (10[i])	100 (3.2[d])
Dairy Slurry	3.00[a] (0.14[f])	50[i] (10[i])	100 (3.2[d])
Dairy Bedded Pack	6.5[f] (1.5[f])	35[i](15[i])	100 (5.0[j])
Beef Finishing Concrete Feedlot	11.8[a] (3.9[a])	35[i](15[i])	100 (10[j])
Beef Finishing Deep Pit	4.68[b] (0.50[b])	60[i](10[i])	100 (3.2[d])
Turkey	22[a] (10[b])	55[h] (5[h])	100 (10[j])
Layer	37.3[a] (2.3[f])	55[h] (5[h])	100 (15[j])

[a] (ASABE, 2005) [b] (Wilson, n.d.) [c] (Hatfield et al., n.d.) [d] (Dougherty et al., 2022) [e] (Lorimor et al., 2004) [f] (Dou et al., 2001) [g](Arnold, 2021) [h](Mallarino & Sawyer, 2023), 2008) [i] used best professional judgement based on (Andersen, 2025), [j](Norman-Ham et al., 2008)

Table 2. Manure N volatilization estimates for different manure application methods.

Application Method	Volatilization (% of Total N) Ave. (St. Dev.)
Injection	1 (1)
Surface Application with Immediate Incorporation	3 (1)
Surface Application with No Incorporation	17 (8)

All numbers above come from (Mallarino & Sawyer, 2023)

Table 3. Estimated N supply effectiveness with different manure application timing.

Application Timing	N Effectiveness
Fall	76 (8)
Spring	100 (6)
Sidedress	119 (12)

All numbers above come from (Willsea, 2025)

Stochastic N Supply Model

Plant-available N supplied by manure was estimated as:

$$M_N = C_N \times V_A \times U \times (1 - V) \times A_N \times S_f \quad (1)$$

Where
M_N is the mass of plant-available N supplied (kg N/ha)

C_N is the total N concentration in the manure (kg N/Mg)

M_A is the mass of manure applied (Mg/ha)

U is the uniformity transverse to the direction of travel (knife-to-knife variability for liquid manures)

V is the fraction of N lost to volatilization (values of 0-1)

A_N is the fraction of N that is 1st year plant available (values of 0-1), i.e., the fraction of nitrogen anticipated to cycle through a form where plants could use it, during the 1st growing season after application.

S_f is a seasonal timing factor used to adjust N supply relative to losses caused by application timing

Monte Carlo Simulation
Each simulation began by selecting a manure type, application timing, application method, and crop rotation. Target N application rates ranging from 11.2 to 448 kg N ha^{-1} (10 to 400 lbs N $acre^{-1}$) were evaluated in 11.2 kg N ha^{-1} (10 lbs N $acre^{-1}$) increments.

For each target rate, the model generated 3,000 Monte Carlo realizations with a unique random normal distribution (using NumPy and SciPy) for each of the above-mentioned variability terms (nutrient content, volumetric application rate, N availability, volatilization losses, and application uniformity) to estimate the available N applied. Each parameter was treated as an independent stochastic variable; we recognize that in some situations these parameters may be linked, i.e., greater volumes of application could lead to poorer injection and, as a result, have higher ammonia volatilization and reduced nitrogen availability, or higher application rates might reduce knife-to-knife variability, but such linking is beyond the scope of our work.

Where necessary, all distributions were truncated to ensure they remained within physically possible bounds. For example, the N content and the application rate were always 0 or above. N availability and volatilization were limited between 0-100% of the applied N.

Application uniformity can be defined as the variability of the spread pattern transverse to the direction of travel as the manure is put on the field. Within each realization, application uniformity was further simulated 400 times to represent row-to-row variability for liquid manure applicators or transverse variability across solid manure spreaders. These nested simulations produced distributions of plant-available N delivered to individual crop rows. We required the total flow an individual corn row received via

application uniformity to be greater than 0 to reflect a physical reality. Forcing values to be greater than 0 artificially causes the average to be higher. To correct for this, we rebalanced to ensure input average.

Simulation sizes of 3,000 Monte Carlo realizations and 400 within-field uniformity realizations were selected after convergence analysis demonstrated stable estimates of economically optimal N rates at these simulation thresholds (Appendix A).

Following each simulation, plant-available N was calculated using Equation (1) and passed to the crop yield and economic models.

Crop Yield Response

Crop yield response to plant-available N was represented using the Mitscherlich equation (equation 2) (NRC, 1961). Maximum yields were assumed to be 12.62 Mg ha^{-1} for corn following soybean and 11.48 Mg ha^{-1} for continuous corn, based on average yield form the USDA Iowa yield statistics from 2012–2022. The Mitscherlich response parameters were fitted to N response curves from the Main Region of Iowa in Iowa State University Corn Nitrogen Rate Calculator (ISU 2004). Separate equations were developed for corn following soybean and continuous corn and assume that yield will be limited by N supply (equations 3 and 4).

$$Y = 100(1 - exp[-c(x + b)]) \quad (2)$$

where Y is the percent of maximum yield,

x is the N application rate (kg N ha^{-1}),

b is a constant that estimates the amount of soil-derived available N (kg N ha^{-1}),

c is the Mitscherlich effect factor (ha kg^{-1} N).

$$Y = 100(1 - exp[-0.0166(x + 63.59)]) \quad (3)$$

$$Y = 100(1 - exp[-0.0120(x + 38.57)]) \quad (4)$$

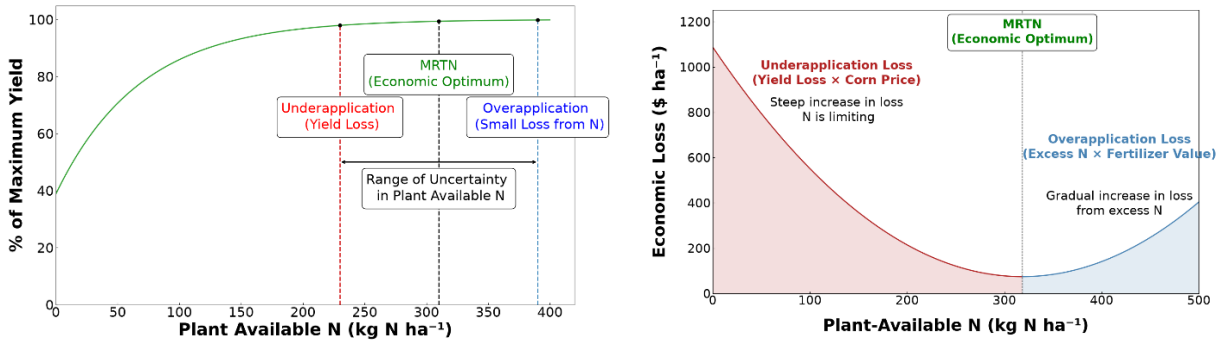
The resulting yield curves assume N is the limiting nutrient and eliminates impacts of variation in the crop demand N supply so the focus can be entirely on uncertainty introduced by manure.

Economic Evaluation

For each simulated realization, the amount of plant-available N supplied was compared with the EONR from MRTN which was 168 kg N ha^{-1} (150 lbs. acre^{-1}) for corn following soybean and 224 kg N ha^{-1} (200 lbs. acre^{-1}) for continuous corn (Sawyer et al., 2006). When plant-available N exceeded EONR, economic loss was calculated as the value of excess N using a fertilizer replacement value of \$0.88 kg^{-1} N (Baum et al., 2025). When plant-available N was below MRTN, economic loss was calculated as the reduction in

grain yield relative to MRTN multiplied by a corn price of \$0.16 kg^{-1} (Baum et al., 2025). While newer data for Iowa yield response has been developed (Iowa Nitrogen Initiative, 2024), our objective was to evaluate the influence of manure N supply uncertainty rather than identify a specific optimum N recommendation. The selected yield response functions provide a representative concave relationship between plant-available N and yield, and illustrates conceptually, how the concept would apply to curves of similar shape.

The asymmetric nature of these economic losses is illustrated conceptually in Figure 2. Because crop yield exhibits diminishing marginal returns with increasing N supply, the economic penalty associated with moderate N deficiency exceeds the penalty associated with a similar N surplus. Consequently, uncertainty in manure N supply shifts the profit maximizing application rate toward higher application rates then the economically optimum nitrogen rate.



(a) (b)

Figure 2. Conceptual illustration of how uncertainty in plant-available N creates asymmetric economic losses and shifts the economically optimal N application rate. Panel A illustrates the concave crop yield response to N, where uncertainty produces both under- and over-supplied outcomes around a target application rate. Panel B illustrates the resulting economic loss function, showing that yield losses associated with N deficiency increase more rapidly than costs associated with moderate N excess. This asymmetry creates an uncertainty-induced increase in the economically optimal N application rate (N risk premium)

Expected economic return for each target N application rate was calculated by averaging results across all Monte Carlo realizations for the specified target N rate. A chart of the target N application rates vs dollars lost was fit with a polynomial, and the minimum of this curve was identified as the profit maximizing N application rate. Each simulation scenario was repeated four times and averaged to ensure numerical stability.

Quantifying the Nitrogen Risk Premium

The uncertainty effect was defined as the difference between the profit maximizing rate determined from our model and the economically optimal N application rate generated from the crop response curve. For each manure type, application method, and application timing, the model quantified how uncertainty propagated through N supply, crop response, and economic return to alter the profit-maximizing application rate. By comparing scenarios with differing levels of uncertainty while maintaining identical expected available N supply, the model isolated the effect of uncertainty from changes in mean manure nutrient content.

Statewide Water Quality Assessment

The environmental implications of uncertainty-driven N application were evaluated using the relationship between N application rate and drainage nitrate concentration developed by (Lawlor et al., 2008). Economically optimal application rates predicted by the stochastic model were compared with baseline recommendations for each manure type under continuous corn and corn-soybean rotations. Predicted nitrate concentrations were converted to nitrate leaching losses assuming 15 cm of annual drainage (1,524 m^3 ha^{-1}) based on best professional judgment and a midpoint between (Iowa Nutrient Research Center, 2020) and (Helmers et al., n.d.). Per-hectare losses were then extrapolated to statewide impacts using Iowa crop rotation statistics from the USDA, manure use by livestock sector(Andersen & Pepple, 2017), and the proportion of cropland receiving manure applications (Bynum, 2026). This analysis estimated the statewide nitrate reduction and economic value achievable by eliminating uncertainty in manure nutrient supply.

RESULTS AND DISCUSSION

Uncertainty in manure nitrogen supply increases the economically optimal nitrogen rate

The primary objective of this study was to quantify how uncertainty in manure N supply influences the profit maximizing nitrogen rate relative to the economically optimal N application rate. Across all manure types, application methods, timings, and crop rotations, increasing uncertainty systematically increased the profit-maximizing N application rate (Figure 3). The increase occurred despite no change in the expected manure N supply, demonstrating that uncertainty alone alters economically optimal management decisions. If the expected commercial equivalency of manure remains unchanged, but the standard deviation of that equivalency increases (i.e., the uncertainty), so does the economically optimal N rate.

The magnitude of this uncertainty-induced shift depended on the combined variability of manure N supply (eq. 1). Figure 3 shows a linear relationship between the summed coefficient of variation of the manure N supply components and the increase in economically optimal N rate. When we look at individual manure sources and application types, this linear trend with variability becomes clearer. For example, injected deep-pit swine manure applied in the fall to continuous corn had one of the smallest summed coefficients of variation (0.26) and required only an additional 24.5 kg N ha^{-1} to maximize expected profit. In contrast, surface-applied beef feedlot manure without incorporation had a summed coefficient of variation approaching 1.0 and required an additional 69.0 kg N ha^{-1}.

Although increasing variability consistently increased the profit maximizing N rate, the response was sublinear. A four-fold increase in total variability produced slightly less than a three-fold increase in optimum N rate. Our results demonstrate that uncertainty itself creates economic value for additional N application. Rather than representing excessive fertilizer use or an insurance product, the additional N functions as the economically optimal decision against the greater financial penalty associated with N deficiency.

Crop nitrogen demand governs the magnitude of the nitrogen risk premium

The effect of uncertainty depended not only on manure variability but also on the sensitivity of crop yield to N supply. Continuous corn consistently exhibited a larger uncertainty-induced increase in economically optimal N rates than corn following soybeans (Figure 3). Because the return from the next unit of N input is greater for corn following corn than corn following soybean, the uncertainty in manure N leads to a greater change in the profit maximizing N rate in continuous corn than in corn following soybean.

Although the MRTN determines the location of the economically optimal N rate, the magnitude of the uncertainty effect is governed primarily by the local curvature of the yield response function around that optimum. Steeper yield response curves (as seen in continuous corn) increase the economic penalty of underapplication, thereby increasing the N risk premium, whereas flatter response curves (as in corn following soybean) reduce sensitivity to uncertainty. This relationship helps explain why continuous corn exhibited greater sensitivity to manure variability than corn-soybean rotations despite similar sources of uncertainty. Likewise, production environments with lower or more variable indigenous N supply or greater seasonal N losses would be expected to exhibit larger uncertainty effects similar to continuous corn.

An interesting example of continuous corn's greater sensitivity occurs for sidedress application (Figure 3). Despite sidedress being more variable than spring (see table 3), the trendlines show that the closer an application is to the growing season, the less it is affected by variability. In continuous corn, sidedress and spring application have near-identical trendlines, whereas sidedress application diverges more substantially from spring application in corn-soybean rotations. The steepness of the continuous corn yield response relative to corn following soybean leads to the higher variability in sidedress N supply having a greater impact on optimum N rate than in the corn-soybean rotation.

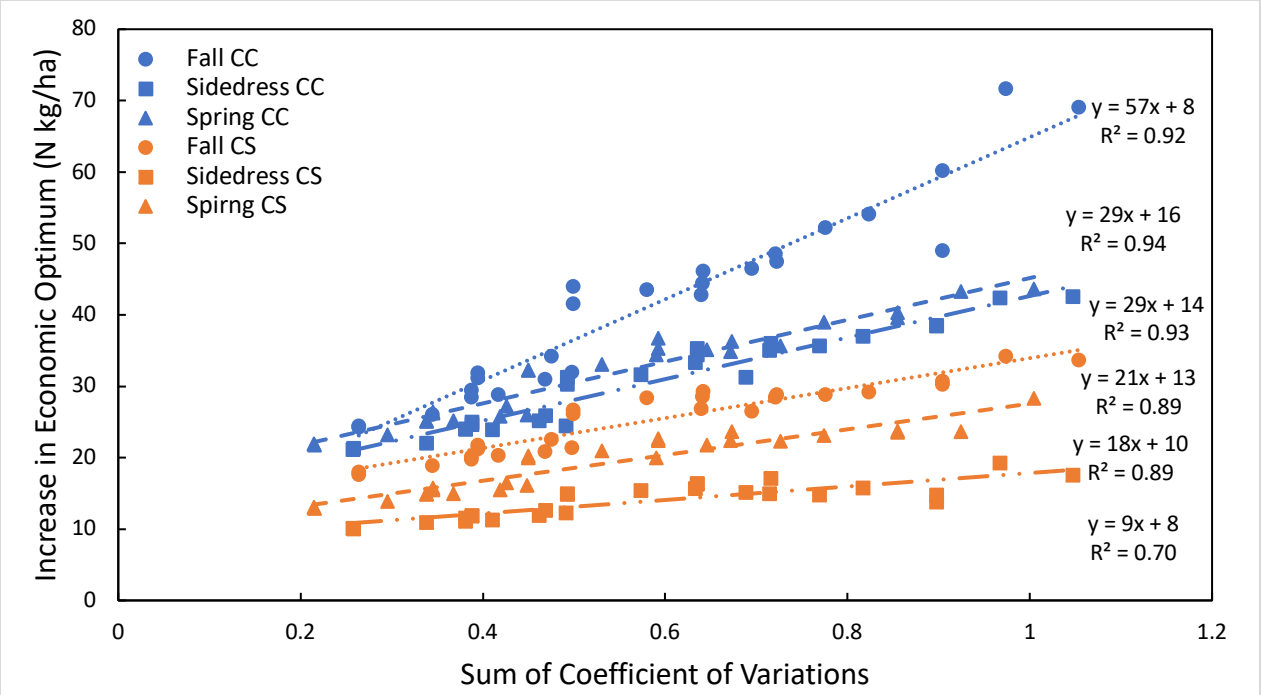


Figure 3. The increase in economic optimum N application rate as a function of the summed coefficient of variations of manure N supply terms. Continuous corn (CC) blue, corn-soy rotation (CS) orange. Fall application timing circles, sidedress application timing squares, and spring application timing triangles

Economic value of reducing manure uncertainty

Because the profit maximizing N rate increased with uncertainty, the associated economic losses also increased nearly linearly (Figure 4). Unlike the profit maximizing N rates, however, economic losses were relatively insensitive to application season. Again, we saw that continuous corn was more sensitive than corn-soybean rotation, suggesting that economic loss was also related to the curvature of the nitrogen response curve and the total uncertainty in fertilizer N supply. Our work suggests that increasing N application rates is the economically optimal strategy for avoiding substantially larger potential losses associated with yield reductions.

These results provide a direct framework for valuing technologies that improve consistency in manure nutrient delivery. Based on Figure 4, reducing the total coefficient of variation by 0.1 generates an estimated value of approximately \$18 ha^{-1} (\$7 $acre^{-1}$) for continuous corn and \$13 ha^{-1} (\$5 $acre^{-1}$) for corn following soybean. These values represent the maximum economic benefit achievable through reductions in uncertainty and therefore provide practical benchmarks for evaluating technologies such as improved manure sampling, precision application systems, real-time nutrient sensing, automated flow control, or even anaerobic digestion to create a more consistently available nutrient product.

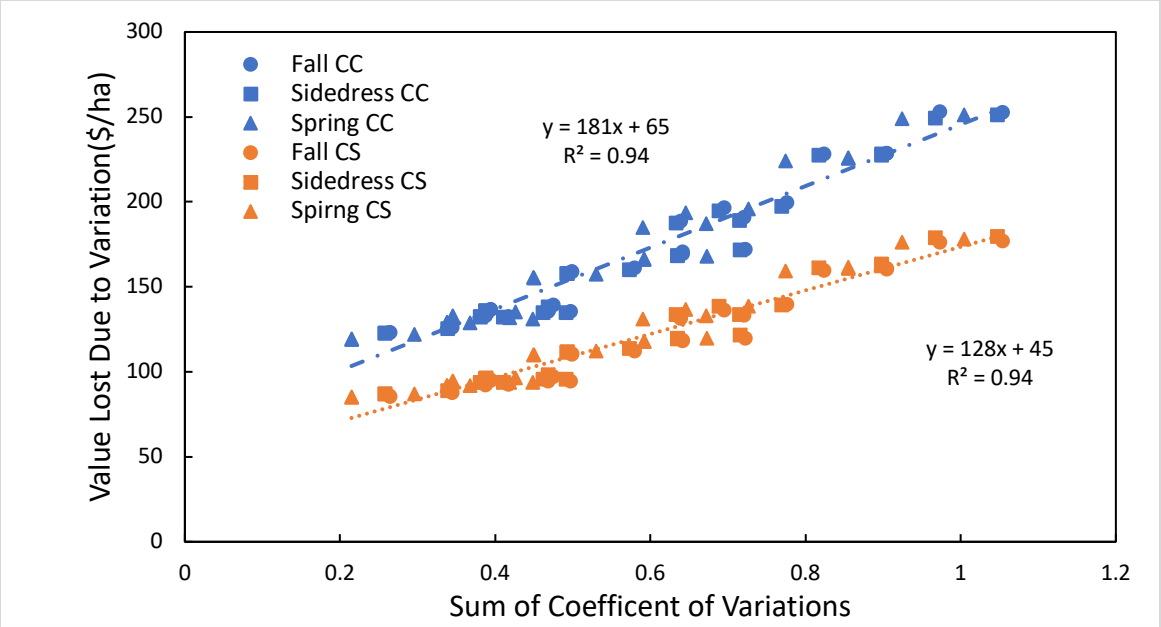


Figure 4. The value lost due to variation of manure in $ per ha as a function of the summed coefficients of variation in manure N supply. Continuous corn (CC) blues, corn-soy rotation (CS) orange. Fall application timing circles, sidedress application timing squares, and spring application timing triangles. The loss is calculated using N at $0.88/kg and corn at $0.16/kg.

Relative importance of individual uncertainty sources

Although most uncertainty sources contributed similarly to the overall N risk premium, application uniformity behaved differently from the remaining model components (Figure 5). Unlike manure nutrient concentration, N availability, flow uniformity, volatilization, or seasonal effectiveness, application uniformity redistributes N spatially rather than changing the total amount of N applied.

As application variability initially increased, economically optimal N rates also increased because greater spatial variability produced more areas of N deficiency. However, beyond approximately 40% variation, the economically optimal N rate declined. At these high levels of spatial variability, additional N increasingly accumulated in already over-fertilized portions of the field rather than improving deficient areas. Consequently, the inefficiency associated with poor application uniformity outweighed the economic benefit of increasing application rates. In essence, in situations with variation greater than 40%, the cost of applying extra N outweighed any potential yield gained.

Differences among manure types were also influenced by their inherent variability. Beef feedlot manure exhibited the largest N risk premium because it possessed the highest overall coefficient of variation, followed by poultry and swine manures. However, these differences became progressively smaller as application uniformity deteriorated, indicating that severe spatial variability eventually dominates all other sources of uncertainty.

These findings demonstrate that not all sources of uncertainty should be managed equally. Technologies that reduce variability in nutrient concentration or improve nutrient

estimation directly reduce uncertainty in plant-available N supply, whereas technologies that improve application uniformity primarily reduce spatial inefficiency.

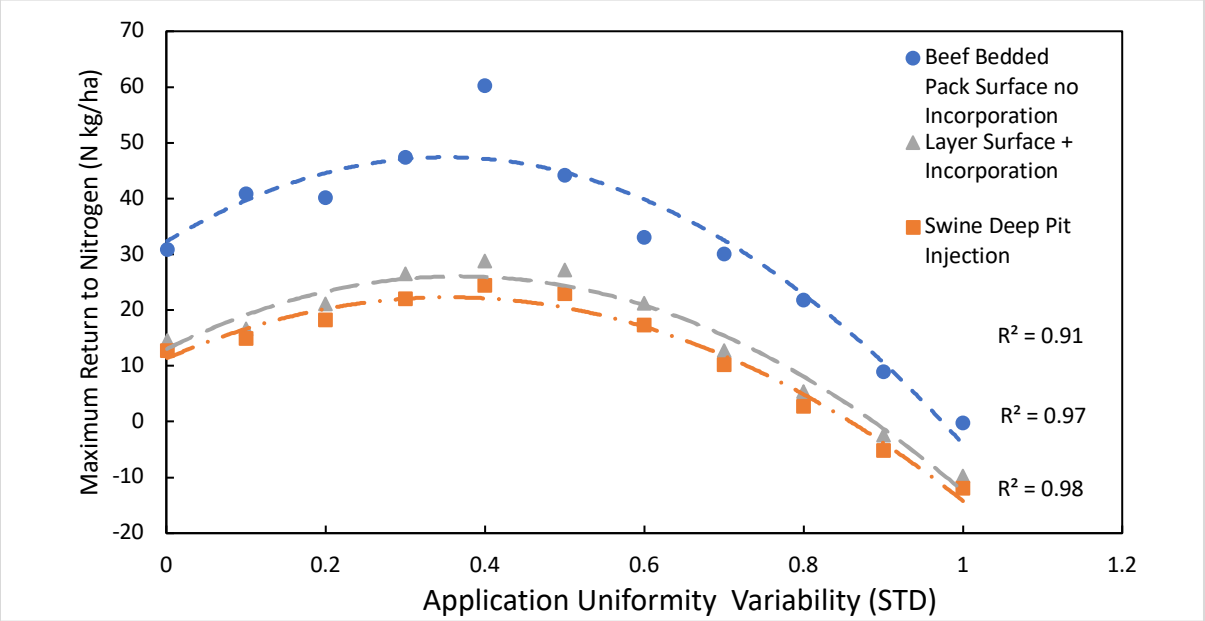


Fig. 5. The economically optimal N application rate relative to the ideal rate as a function of manure application uniformity. The trendlines are a second polynomial. Beef Bedded Pack SNF blue circles, Layer SF gray triangles, and Swine Deep Pit I orange squares. The manure types were selected for their prevalence and to represent all the tested manure application methods. Continuous corn fall was used for all three.

Environmental implications of uncertainty-driven N application

The uncertainty-induced increase in profit maximizing N application rates also produced measurable environmental consequences. Because nitrate leaching increases disproportionately with N application rate (Lawlor et al., 2008), relatively modest increases in economically optimal N (Table 4) resulted in substantially larger increases in predicted nitrate loss (Table 5).

Continuous corn consistently exhibited greater nitrate losses than corn-soybean rotations across all manure systems. Although continuous corn represents a much smaller proportion of Iowa's manure-applied acreage, its greater N demand and steeper yield response produced disproportionately larger uncertainty-induced increases in N application and subsequent nitrate leaching.

Statewide, the model estimated that if manure was used as the only fertility source, uncertainty in manure N supply contributes approximately 13 million kg of nitrate loss annually, representing roughly 8% of Iowa's estimated annual nitrate load (Iowa Department of Agriculture and Land Stewardship et al., 2026). These results indicate that uncertainty itself represents a measurable environmental cost independent of average N availability.

Overall, these findings demonstrate that reducing uncertainty has value beyond improving nutrient use efficiency. Technologies that make manure nutrient delivery more predictable reduce the N risk premium, lower economically optimal N application

rates, and decrease environmentally driven N losses without requiring reductions in crop productivity.

Table 4. Estimated nitrate leaching due to uncertainty and variability in manure N supply causing an increased economic optimum N rate.

Manure Type	Application Method	Rotation	Application Rate (kg N/ha)	NO_3-N Leaching above Baseline (kg NO_3-N/ha)	Area Impacted (ha)	NO_3-N Leaching above Baseline (Mg NO_3-N)	Dollars Lost due to Variation ($/ha)
Base Application	-	CC	296	-	-	-	-
	-	CS	222	-	-	-	-
Swine Finishing Deep Pit	Inj.	CC	321	13	263,174	3,357	123
	Inj.	CS	240	4	1,381,665	5,793	86
Dairy Slurry	Inj.	CC	328	17	10,326	179	137
	Inj.	CS	244	5	54,215	281	95
Beef Concrete Feedlot	Surface, NI	CC	365	46	29,415	1,361	253
	Surface, NI	CS	256	9	154,431	1,321	177
Layer	Surface, NI	CC	328	17	3,129	6	136
	Surface, NI	CS	243	5	16,428	83	94
Turkey	Surface, NI	CC	348	32	6,884	219	200
	Surface, NI	CS	251	7	36,143	258	140

CONCLUSION

Our study demonstrates that uncertainty in manure N supply systematically increases the profit maximizing N application rate. Because crop yield responds to N with diminishing marginal returns, producers face a greater economic penalty from N deficiency than from moderate N oversupply. Consequently, uncertainty creates a manure risk premium, an economically rational increase in N application intended to reduce the risk of under-fertilization. Importantly, this increase occurred despite no change in the expected manure N supply, indicating that uncertainty alone alters economically optimal management decisions.

The magnitude of this manure risk premium increased with the combined variability in manure nutrient concentration, N availability, volatilization losses, application timing, and application method. While most sources of uncertainty contributed similarly to this effect, application uniformity behaved differently because it redistributed N spatially rather than altering the total amount supplied. These findings demonstrate that technologies improving manure consistency create value not only by conserving nutrients but also by making nutrient delivery more predictable.

The consequences of uncertainty extended beyond farm profitability. Profit maximizing N application rates resulted in greater predicted nitrate leaching, demonstrating that uncertainty carries both economic and environmental costs. At the statewide scale, the model suggests that reducing uncertainty in manure N supply could simultaneously lower crop production costs and reduce nitrate losses. Thus, improving consistency in manure nutrient delivery should be recognized as a nutrient management strategy alongside practices that increase average N recovery or reduce nutrient losses.

Although the model assumed that crop N requirements were supplied entirely by manure and considered only a single growing season, the underlying concept extends well beyond these assumptions. Future work should evaluate systems that combine manure and commercial fertilizer, incorporate residual and legacy N effects, and account for additional sources of uncertainty, including spatial and temporal variability in crop N demand. Because the framework isolates the economic consequences of uncertainty independent of changes in mean nitrogen supply, it can also be applied to evaluate emerging technologies such as real-time nutrient sensing, automated application control, manure processing, and precision nutrient management all of which have the potential to make manure N supplying power more predictable.

More broadly, this work suggests that manure management technologies should be evaluated not only according to their ability to increase average nutrient availability or reduce nutrient losses, but also according to their ability to reduce uncertainty in nutrient delivery. Reducing uncertainty has independent economic and environmental value because it allows producers to apply manure closer to the true economic optimum, lowering the manure risk premium while maintaining crop productivity. In this way, uncertainty is not simply a management inconvenience, it is itself a measurable cost of manure management.

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Supplemental Materials: Monte Carlo Convergence Analysis

A convergence analysis was conducted to determine the number of Monte Carlo realizations required to produce stable estimates of economically optimal nitrogen application rates and expected profit. The analysis was performed using the scenario with the greatest overall uncertainty (surface-applied beef feedlot manure without incorporation, applied in the fall to continuous corn) because this represented the most computationally demanding case.

Simulation sizes of 250, 500, 1,000, 1,500, 2,000, and 3,000 Monte Carlo realizations were evaluated. Each simulation size was independently repeated four times to estimate the variability in predicted economically optimal nitrogen application rate and expected profit. The resulting standard deviations are presented in Figures A1 and A2. As expected, increasing the number of realizations progressively reduced the variability of the model outputs, although the rate of improvement diminished with increasing simulation size. Differences between 2,000 and 3,000 realizations were minimal, with standard deviations differing by only \$0.22 ha^{-1} for expected profit and 0.48 kg N ha^{-1} for the economically optimal nitrogen application rate. Because additional realizations produced negligible improvements in numerical precision while substantially increasing computation time, 3,000 Monte Carlo realizations were selected for all simulations reported in this study.

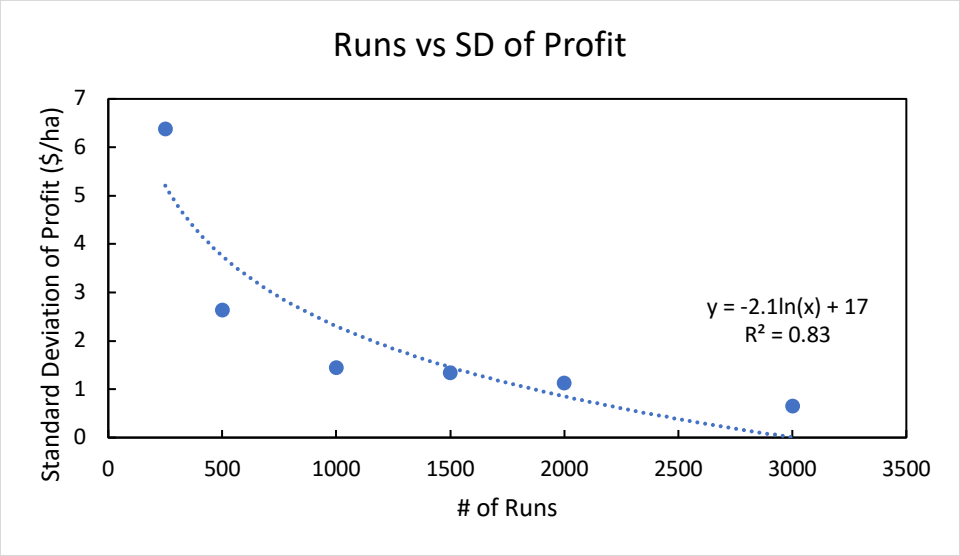


Fig. A1 The standard deviation of profit on the y axis vs the number of runs done for our model on the x axis. The trendline is a natural log function, with each data point representing a different number of runs.

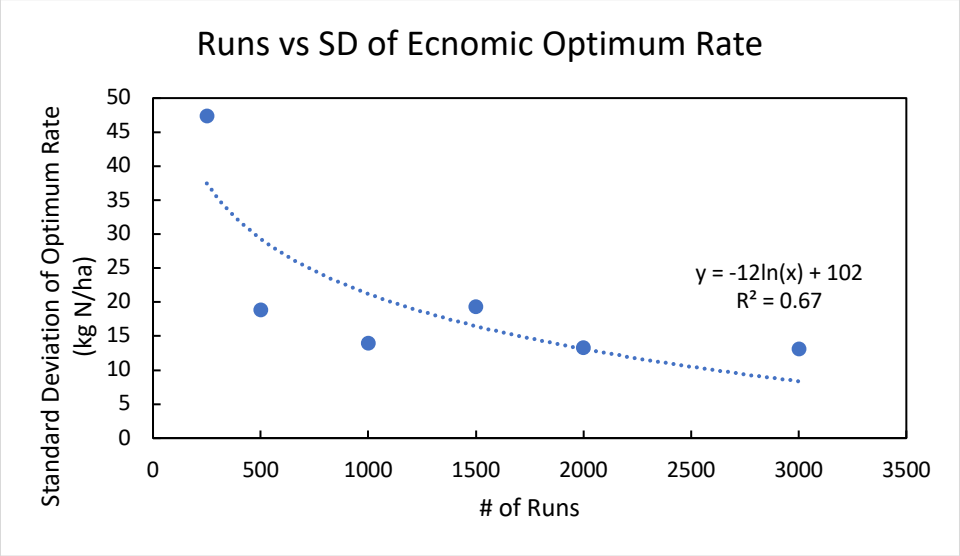


Fig. A2 The standard deviation of kg N/ha on the y axis vs the number of runs done for our model on the x axis. The trendline is a natural log function, with each data point representing a different number of runs.