Heterogeneous Nitrogen Losses: Cost Effective Analysis of Changes in Management in South Dakota

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Abstract

The loss of nitrogen fertilizer into the atmosphere and waterways is of increasing concern for policy makers. This study conducts a cost-effective analysis (CEA) to determine the best strategies, and areas, to reduce nitrogen losses in South Dakota. This form of analysis is done by spatially comparing the amount of reductions per acre across the state, assuming alternative mitigation strategies and adoption rates. Using environmental factors, (Climate type, soil texture, soil organic carbon, soil drainage, soil pH and crop type), and management decisions (no till, conventional till, reduced till, crop rotations, and application timing), we assess the best areas and methods in South Dakota that can be targeted with management changes to gain the most cost effective continuous improvement in nitrogen losses. The Environmental Policy Integrated Climate (EPIC) model was used to simulate the homogeneous response units to changes in nitrogen management practices and assess nitrogen losses. Simetar was then used to derive certainty equivalence values for changes in nitrogen loss and producer returns from changes in nitrogen management.

Keywords: Cost-effective analysis, nitrogen losses, management decisions.

Introduction

In modern agriculture, the use of nitrogen fertilizers to boost crop production is a common practice. However, the application of fertilizer can result in significant externalities including: contaminating water bodies like rivers, lakes and oceans, contaminating ground water, and also polluting the atmosphere through the emission of nitrous oxide. Changes in nitrogen management can reduce these losses. The purpose of this study is to determine the cost effectiveness of various nitrogen application strategies to reduce nitrogen losses.

Nitrous oxide (N_2O), one of the main greenhouse gases, is emitted from both natural and human sources. Natural sources like oceans and soils under natural vegetation are responsible for 62 percent of N_2O in the atmosphere whereas human activities such as agriculture and fossil fuel combustion contribute 38 percent of total emissions (Denman, K.L., et al, 2007). Of the various human activities which contribute to nitrous oxide emissions, agriculture is the largest source. According to the Environmental Protection Agency (EPA), agricultural soil management through the application of synthetic fertilizers accounted for about 74 percent of the total U.S. N_2O emissions in 2013.

Alternatively, nitrogen loss contaminates waterways and groundwater. It is estimated that N exported from agricultural ecosystems to waterways, as a percentage of fertilizer inputs, ranges from 10% to as high as 80% depending on the soil type (Howarth et al., 1996). This makes the timing and quantity of N applied important management decisions for producing crops efficiently and with minimal externalities. Sharpley and Rekolainen (1996) states that the greater proportional losses of nitrogen into aquatic ecosystems may result from higher nitrogen application rates and less flexibility in the timing of applications, thus creating varying costs to altering fertilizer management across production regions and types.

The total estimated costs of externalities from nitrogen loss ranged between $81 to $441 billion/year or $108.61/kgN in the early 2000s (Sobota et al., 2015). This implies that the costs to mitigating nitrogen losses through effective management practices may be less than the benefits from improved quality of air and water while sustaining sufficient crop production.

Research Objectives

The research objectives of this project are:

- Model and compare the effects of various management choices, categorized as treatments, on yield and mitigation nitrogen losses.

- Perform stochastic dominance to determine best nitrogen management practices to reduce N losses and maintain crop returns.
- Conduct a Cost-Effective Analysis (CEA) to determine the best strategies and areas to reduce losses from nitrogen fertilizer application.

Significance of the Study

The agricultural sector has a significant role to play in the mitigation of GHGs and reducing nitrogen in waterways. The knowledge from this research enables policy makers to make more informed decisions regarding nitrogen best management practices. It is also aimed at helping ag producers make effective management decisions to increase their productivity and improve environmental quality (Claassen & Ribaudo, 2016).

Research Design

This study uses historical climate data, fertilizer applications and management to simulate nitrogen losses and effects to crop production over a period of thirty years. The management data was obtained from the USDA – ARMS dataset. The EPIC model simulates crop growth and potential yields which can be used in strategic planning and policy making. Simetar calculates stochastic dominance and orders management preferences. The output variables considered for this study are annual crop yield, nitrogen loss from sediment, nitrogen loss to subsurface and annual soil carbon nitrogen. Further details of the variables used in this research are discussed below.

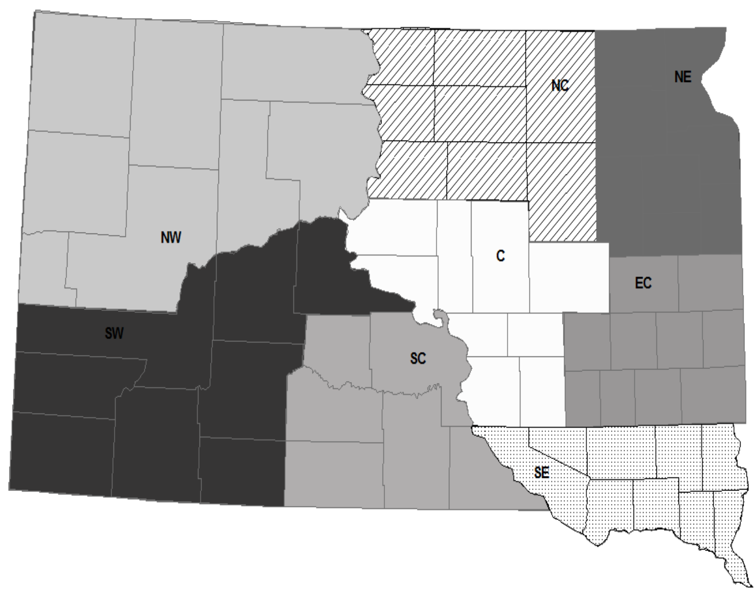
Study area

This research is focused on crops grown in the state of South Dakota. Corn, soybeans and spring wheat are the predominant crops grown in South Dakota, comprising 68.4% of the total crops planted (USDA – NASS, 2013). Corn is the most dominant crop accounting for 35.1%, followed by soybeans which makes up 27.1%. The type of soils found and used to grow crops in the state are generally loam, sandy loam with dark to black soil surfaces and limy sub soils (USDA Soil Survey Report, 2004). Other crops cultivated in South Dakota include sunflower, sorghum, beans, field pea, barley and oats. Pasture and hay are also produced on a large scale.

Climate Data

Weather data that can be simulated to determine nitrogen losses and production can be historical daily weather or can be generated from long-term averages. Locations and spatial homogeneity of weather depend on the number of weather stations representing a particular area. EPIC is a dynamic model which allows the user to specify two weather files: the weather and wind weather files. If the regular weather and wind station identification parameters are not specified, EPIC will use the latitude and longitude data simulated into the model and choose the closest weather and wind stations. For this study, the monthly climate data used are the mean and standard deviation of maximum air temperature (^oC), mean and standard deviation of minimum air temperature (^oC), mean (mm), standard deviation (mm), and skewness of precipitation, the probability of wet day after dry day and the probability of wet day after wet day, number of days of rain per month, maximum half hour rainfall (mm), mean solar radiation (MJ/m^2 or Langley), mean relative humidity (fraction) and mean wind speed (m/s). The eight weather stations for South Dakota: North Central (NC), North East (NE), North West (NW), Central (C), East Central (EC), South East (SE), South Central (SC), and South West (SW) are represented in the figure below:

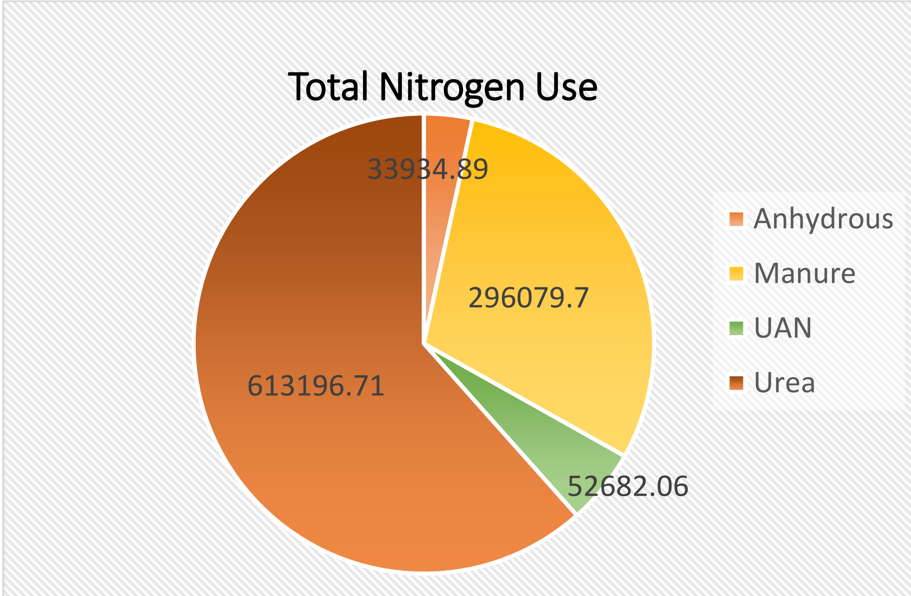
Figure 1: South Dakota weather stations



Nitrogen application

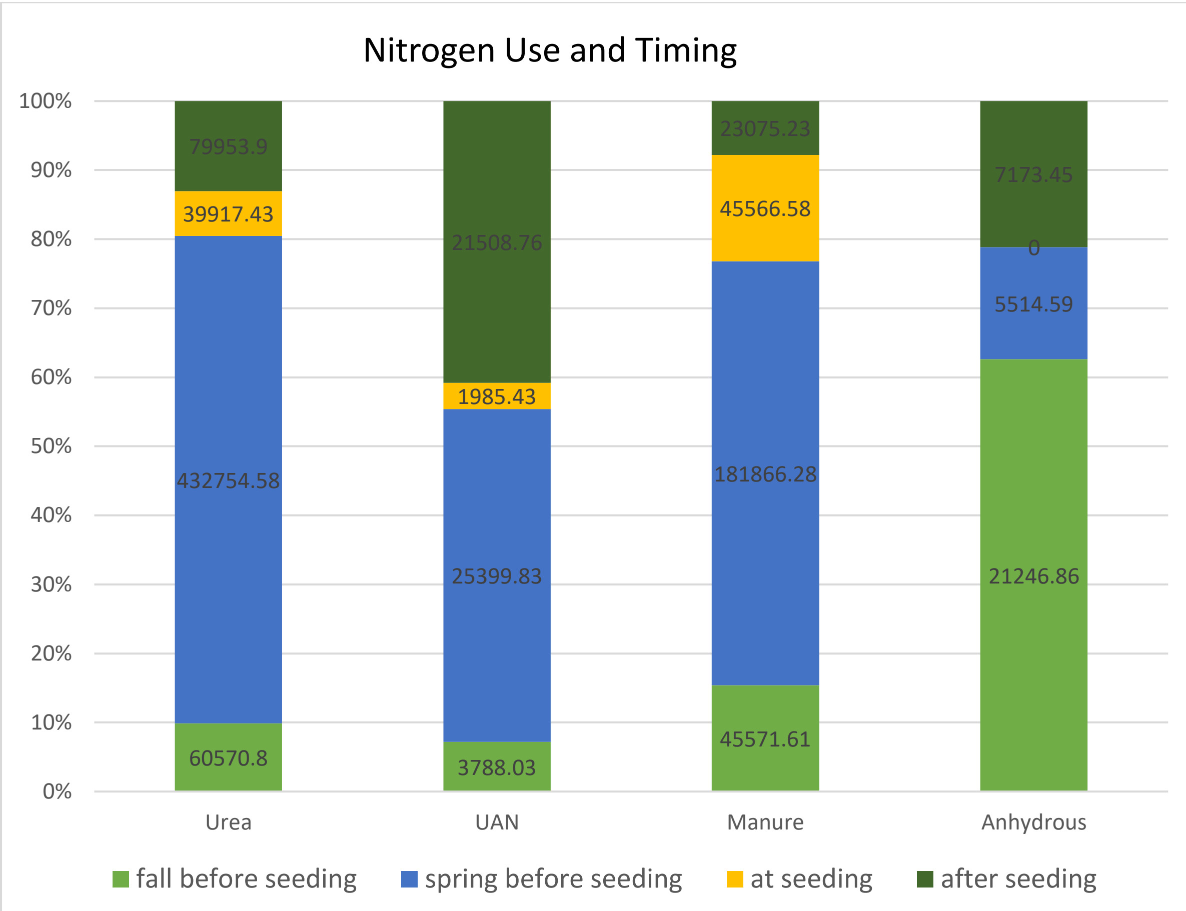
The application of fertilizer was categorized into the quantity and timing of application and its effect on crop yield, leaching and run-off. To do the analysis, data on the types of fertilizers used by South Dakota farmers was extracted from USDA-ARMS dataset. Generally, urea is the most used fertilizer in South Dakota constituting 62% of total fertilizer use (USDA-NASS, 2010). The remaining nitrogen types include anhydrous ammonia, urea ammonium nitrate (UAN), and other types of fertilizers (usually manure) which made up 3.4%, 5.2%, 29.7% respectively. The quantities of fertilizer use is shown in the pie chart below.

Figure 2 Total nitrogen use (tons)



To account for the timing of fertilizer application which will help in setting up the control treatment, the timing of all four categories of fertilizers was analyzed to ascertain which fertilizer was used most at a particular time period. The time periods were fall before seeding, spring before seeding, at seeding, and after seeding. A pictorial view is shown in the bar chart below.

Figure 3 Nitrogen Use and Timing



From figure 3 above, it can be concluded that urea is mostly used by farmers both before and a few weeks after planting. It contributes approximately 67% of the fertilizers used before seeding and 61% of those used after planting. At seeding, other types of fertilizers (largely manure and other nitrogen-based fertilizers) are used.

Data Analysis

The analysis of the data was done using Simetar after using the EPIC model to simulate the yield values and nitrogen losses over a thirty-year period. Before Simetar was used for the analysis, the five dominant management strategies were identified and categorized into treatments. The first was the control treatment, which is representative of the dominant method of nitrogen application for farms in South Dakota. The control treatment (T_0) which consists of 75% of nitrogen was placed on the field a few weeks before and at planting. The rest (25%) was applied six weeks after planting. The first treatment (T_1) reduced the amount of fertilizer place on the field before and at planting to 55%. The remaining fertilizer was then (forty-five percent) placed on the field a few weeks after planting. The second treatment (T_2) comprised twenty-five percent (25%) of the fertilizer being applied a few weeks before and at planting whereas majority (75%) was applied six weeks after planting. The third treatment (T_3) maintained the mode of fertilizer application from the control but changed the tillage from conventional to no-till. Lastly, treatment four (T_4), auto-fertilization, was simulated in the EPIC model to provide crops with just the right quantity of fertilizer needed. After deciding on the various treatments to implement, we further ranked the slopes of the farms within the counties into five distinct slopes (slope rank zero to slope rank four). Slopes were calculated as the vertical distance (height difference) divided by the horizontal distance multiplied by 100. Lands with slope between 0% to 1% were categorized slope rank zero. Slope ranks one, two, three and four were lands with slope between 1.1% to 2%, 2.1% to 2.5%, 2.6% to 3.5% and 3.6% to 5% respectively. Following the simulation with EPIC model, the results for the interested variables (annual output, crop growth, crop yield, and soil carbon) were merged together using SAS. Simetar was then employed to calculate the first and second order stochastic dominance of each of the management decisions and also to simulate the certainty equivalence.

Empirical Results

The main objective of this study is to model and compare the effects of various management choices on yield and nitrogen losses. The second objective is to conduct a stochastic dominance analysis to determine the best management practices and perform a cost-effective analysis to discover most cost effective ways of mitigating nitrogen losses. To make the most effective management decisions regarding yield and nitrogen losses, all sixty-six counties in SD were ordered and paired in terms of slope ranks and treatments. After using EPIC model to simulate the yield over a thirty-year period, the yield values were ranked in order of preference (from most preferred to least preferred) within each of the counties. To make a better assessment of which treatment is more effective, the analysis considered the best ranked treatment on average within each slope rank. As expected, treatment four (T_4, auto-fertilization treatment) was the most dominant treatment among the slope ranks. However, this (T_4) may not be achievable given current technology because it is costly for producers to know the specific amount of fertilizer that the crops need at a given point during the crop production cycle. Further it may be cost prohibitive to make multiple nitrogen applications during the crop production cycle.

Stochastic dominance was used to order the treatments to choose the best treatment. This is defined as the process of ranking decisions based on the probabilities of two or more random variables. A random variable X has a first order stochastic dominance over another variable Y if for any outcome 'p', X gives at least as high a probability of receiving p as does Y. A random variable X has a second order stochastic dominance over Y if X is more predictable, that is, less risky, and has at least as high a mean as Y.

Considering slope ranks zero to three, and implementing the stochastic dominance analysis, treatment two (T_2) was the preferred treatment. This treatment reduces pre-plant and at plant nitrogen application to twenty-five percent of the total nitrogen application a few weeks and the rest (75%) six weeks after planting. Slope ranks zero and three had similar preferences. They preferred treatment two, treatment one as next best alternative after treatment two, treatment three, then the control treatment (treatment zero) in that order. Slope ranks one and two also preferred treatment two as a better option compared to the rest. Treatment one is the next best option after treatment two just like the cases of slope ranks zero and three. However, slope ranks one and two preferred the control treatment over treatment three. Counties with land categorized as slope rank four chose treatment two as their most preferred choice over treatment four which dominated all other ranks. Treatment one was the third most preferred, followed by the control treatment then treatment three, as the least preferred.

Table 1 Average Treatment Preferences within slope ranks with respect to yields

Slope Rank	**Most preferred treatment**	**2nd most preferred**	**3rd most preferred**	**4th most preferred**	**Least preferred treatment**
0	Treatment 4	Treatment 2	Treatment 1	Treatment 3	Treatment 0
1	Treatment 4	Treatment 2	Treatment 1	Treatment 0	Treatment 3
2	Treatment 4	Treatment 2	Treatment 1	Treatment 0	Treatment 3
3	Treatment 4	Treatment 2	Treatment 1	Treatment 3	Treatment 0
4	Treatment 2	Treatment 4	Treatment 1	Treatment 0	Treatment 3

To analyze the effect of management choices on GHG emissions, a similar simulation was conducted for total nitrogen loss considering the various treatments. As expected, the auto-fertilization treatment (T_4) stood out as the best treatment across all five slope ranks because it puts the right amount of fertilizer needed by the crop at any point in time thereby minimizing the emission of GHGs. The next best alternative was treatment two. It was also preferred to the other treatments in all the slope ranks except slope rank two where treatment one was preferred to that. The control treatment was the second least preferred treatment in all the slope ranks and the least preferred treatment was treatment three (Table 2). To assess the effect of leaching on total nitrogen loss, the study analyzed the GHG emissions without the leaching component. This was done to determine the effect of leaching on total nitrogen loss from fertilizer application. The result showed that leaching did not affect the amount of total nitrogen loss significantly. The order of preferences remained the same throughout the slope ranks as in Table 2.

Table 2 Average Treatment Preferences within slope ranks with respect to total nitrogen loss

Slope Rank	**Most preferred treatment**	**2nd most preferred**	**3rd most preferred**	**4th most preferred**	**Least preferred treatment**
0	Treatment 4	Treatment 2	Treatment 1	Treatment 0	Treatment 3
1	Treatment 4	Treatment 2	Treatment 1	Treatment 0	Treatment 3
2	Treatment 4	Treatment 1	Treatment 2	Treatment 0	Treatment 3
3	Treatment 4	Treatment 2	Treatment 1	Treatment 0	Treatment 3
4	Treatment 4	Treatment 2	Treatment 1	Treatment 0	Treatment 3

The next objective was to perform a cost-effective analysis which was done by retrieving the certainty equivalent values after constructing a first and second order stochastic dominance. Certainty equivalence is the guaranteed amount of money that an individual would view as equally desirable as a risky asset. In other words, it is the money or return that an individual is willing to accept rather than taking a chance on a higher, but uncertain return. Using Simetar, the certainty equivalent under exponential utility values were computed for all the slope-treatment combinations. To analyze the economic costs and effects of the various treatments, the control treatment was compared to the other treatments to estimate how much a farmer/producer would have to be compensated in order to move from the control treatment to a particular treatment.

Treatment one generally does not need any compensation irrespective of the slope rank but it was almost always second best to treatment two in terms of yield and GHG emission ranking. However, considering treatment two's certainty equivalent values, some counties had to be compensated in order to consider adopting it. In Davison, Fall River, and Hutchison counties for example, farm lands with slope rank zero needed to be compensated ($12 per hectare) in order to be indifferent between the control treatment and treatment two. Aurora and Todd counties were the only two counties with farmlands under slope rank one which needed compensation to be indifferent between treatment two and the control treatment. Under slope rank three, Davison, Todd and Tripp counties had to be compensated with Tripp county needing as much as $22.64 per hectare to be indifferent. The highest number of counties to be compensated under treatment two was found in slope rank four. Coincidentally, treatment two was the most preferred treatment, even ahead of treatment four, in that slope rank. This to some extent explains why farmers/producers predominantly use the control treatment although treatment two produces the greatest yield. As many as eleven counties (Brule, Buffalo, Custer, Davison, Fall River, Faulk, Lyman, Marshall, Minnehaha, Tripp and Turner) have to be compensated to make them indifferent between the control and treatment two. Also, the compensation to be paid can go as high as $36.50 per hectare. Adopting treatment three would be costly due to the fact that most of the counties would have to be compensated and comparatively higher than both treatment two and the control. For farmers/producers to be indifferent to treatment three, the lowest compensation to be paid them is $58.5 per hectare which is $12 more than payments to be made to farmers to make them indifferent considering treatment two. The payments can go as high as $75 /ha which makes treatment three very expensive to adopt. It also rates third best or least preferred among the treatments making it infeasible. With respect to treatment four, it will cost an average of $3 less compared to the amount to be paid when adopting treatment two with regards to farmlands in slope rank zero. However, farmlands in slope rank one will need an average of $4 /ha more than the compensation paid to adopt treatment two. In terms of slope ranks two and three, treatments two and four basically will have to pay the same compensation for farmers to be indifferent to changing from the control treatment. Treatment four will cost $10 more on average compared to treatment two if farmers are to adopt the control treatment.

Table 3 Maximum compensation ($) necessary for farmers/producers to be indifferent to treatments.

Slope rank	Treatment 1	Treatment 2	Treatment 3	Treatment 4
0	0.00	12.18	62.43	9.61
1	0.00	10.53	74.69	14.93
2	0.00	19.79	69.13	18.74
3	0.00	22.64	58.53	22.63
4	0.01	36.48	73.06	46.76

Conclusion

The impact of agricultural management practices are important environmental issues which need to be researched and addressed accordingly. This study focused on the particular management practice of fertilizer application in terms of quantity and timing. The research also considered cost-effective ways to mitigate the emission of GHGs from nitrogen fertilizer application. Findings are expected to help both policy makers and producers make enlightened decisions regarding nitrogen management practices.

One of the major constraints of this research is that the data considered is at the county level so some site-specific impacts may be lost in the analysis. Additionally, the stochastic dominance analyses assumed that producers were risk neutral. This means that further studies assuming risk averse producers can be explored in the future to reveal other dynamics of preference.

Despite the limitations, this research provides significant insight concerning areas in South Dakota to focus emission reduction efforts. It also helps explain the importance of incentivizing and compensating producers in the mitigation of greenhouse gases and the reduction of nitrogen run-off into waterways.

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