The Impact of Improving Nitrogen Use Efficiency on Nitrous Oxide Emissions from Cropland

Xin Zhang[1], Danise Mazerall [1,2], Ruohong Cai [1]

1. Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ;
2. Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ;

Introduction

To mitigate nitrous oxide (N_2O) emissions from the agricultural sector, improving nitrogen use efficiency (NUE) in crop production has been proposed as one of the major pathways (*Davidson, 2012*). Nitrous oxide emissions from crop production can be estimated as the product of the nitrogen fertilizer applied and an emission factor (*IPCC, 2006*). The use of behavioral changes, slow-release fertilizer and fertilizers with nitrification inhibitors, and improvements in crop cultivars can potentially reduce both nitrogen fertilizer application and the emission factor. However, each of these nitrous oxide reduction pathways is associated with large uncertainties, which need to be constrained (*Venterea et al., 2012*).

This study analyzes the impact of adopting NUE improvement technologies on nitrogen fertilizer application rates, nitrogen use efficiency, and farmer's profit on farm and regional scales, assuming the farmer optimizes nitrogen application rates to maximize profit.

Theoretical Model

For a plot with conventional nitrogen management technology, the yield response (*Y*) to nitrogen application (*X*) can be parameterized using a quadratic-plus-plateau yield response relationship, which is commonly used to determine nitrogen fertilization rates (*Cerrato and Blackmer, 1990; Sawyer et al., 2006*)

$$Y = \begin{cases} a + bX + cX^2 & (X \le -b/2c) \\ -b^2/4c + a & (X > -b/2c) \end{cases} \quad (1)$$

In the equation, *a*, *b*, and *c* are the coefficients of the yield response curve, and *a*,*b*>0, while *c*<0. According to Equation 1, X_0=0, Y_0=a; $X_{max} = -b/2c$, $Y_{max} = -b^2/4c + a$.

Assume the farm size is *A* hectares, then the farmer's net profit (π) is

$$\pi = A \cdot (Y \cdot Pr_{crop} - X \cdot Pr_{fert} - Cost_{other}) \quad (2)$$

Pr_{crop} and Pr_{fert} are the prices of the crop sold and the nitrogen fertilizer applied. $Cost_{other}$ are costs like operating costs and overhead, but exclude fertilizer costs (USDA, 2013).

According to *Fageria and Baligar* (*2005*), the apparent nitrogen recovery efficiency (NUE_r) is

$$NUE_r = \frac{Y - Y_0}{X} \cdot NC = (b + cX) \cdot NC \quad (3)$$

NC is the nitrogen content (kg N per kg crop product).

We assume the farmer optimizes their nitrogen fertilization rate ($X_{\pi max}$) to maximize their net profit (π). Their corresponding profit maximizing yield ($Y_{\pi max}$) and net profit ($\pi_{\pi max}$) can then be solved from equations (1) and (2) based on the first order condition that marginal revenue equals marginal cost.

$$X_{\pi max} = -\frac{b}{2c} + \frac{1}{2c} \cdot \frac{Pr_{fert}}{Pr_{crop}} \quad (4)$$

$$Y_{\pi max} = \frac{R^2}{4c} + a - \frac{b^2}{4c} \quad (5)$$

$$\pi_{\pi max} = \left(a - \frac{b^2}{4c}\right) Pr_{crop} - \frac{{Pr_{fert}}^2}{4c} \cdot \frac{1}{Pr_{crop}} + \frac{b}{2c} Pr_{fert} - Cost_{other} \quad (6)$$

$$NUE_{r,\pi max} = \left(\frac{b}{2} + \frac{1}{2} \cdot \frac{Pr_{fert}}{Pr_{crop}}\right) \cdot NC \quad (7)$$

Input Data

We use a yield response function for continuous corn (from a 3-year study in SE Minnesota, reported by *Yadav et al.* (*1997*)) to demonstrate the model analysis and policy implications.

Table 1. Summary of the input data to the model

Parameter	Value	Data Source
Yield response function		
a	7.42×10^3	(*Yadav et al., 1997*)
b	26.2	
c	-0.0640	
Price and cost information		
Pr_cr	0.22 $ kg $^{-1}$	Corn price for USA Hartland in 2011 (*USDA ERS, 2013*)
Pr_fert	0.91 $ kg N $^{-1}$	Anhydrous ammonia price for USA in 2011 (*USDA ERS, 2013*)
Cost_other	1189 $ ha^{-1}	Total cost minus fertilizer cost for corn farm in Hartland in 2011 (*USDA ERS, 2013*)

Optimal Nitrogen Fertilization Rate

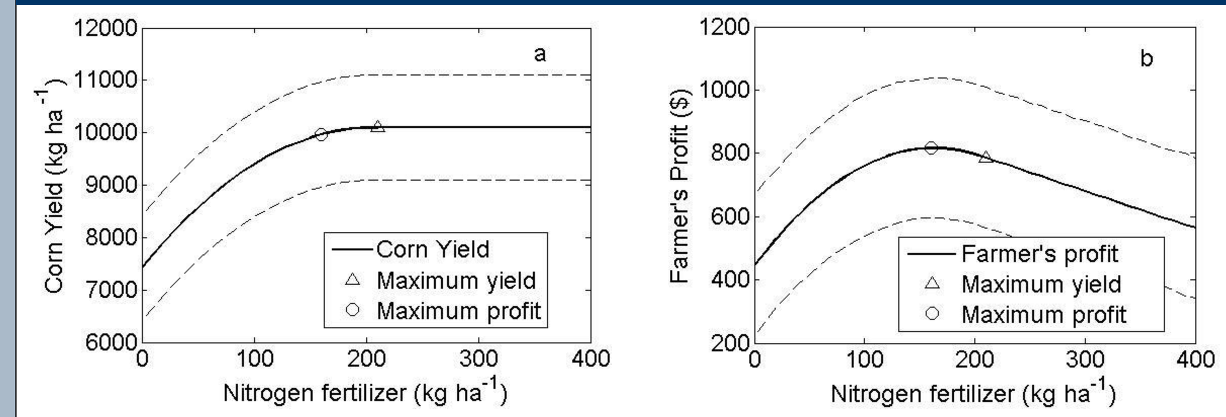

Figure 1. Response of (a) corn yield and (b) farmer's net profits to nitrogen application rates. The circles denote the optimal nitrogen application level determined by a fertilizer to corn price ratio (*R*) of 4.14 in 2011. The optimal nitrogen application level maximizes a farmer's net profit. The triangles denote the nitrogen application rate when yields reach the yield ceiling. The dashed line shows the range of year-to-year variation.

The Impact of Price Change

We choose the 2011 fertilizer to crop price ratio as our baseline ($R_{baseline}$=4.14). By varying our baseline price ratio from 0.5 to 4 times of the baseline price ratio, the (a) optimal nitrogen fertilizer input, the (b) corresponding nitrogen use efficiency and (c) net profit change accordingly. Under the same environmental conditions and nitrogen management technology, an increase of the fertilizer-to-crop price ratio (increase in fertilizer price or decrease of crop price) leads to a decrease in nitrogen application rates and profit, and an increase in NUE.

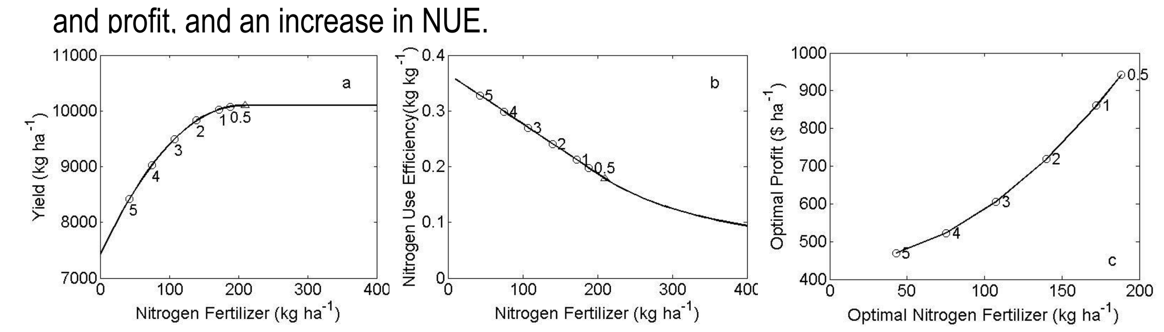

Figure 2. Optimal nitrogen application rates and resulting yield, NUE, and profits at different price ratios. The numbers in the graphs denote the relative change relative to the baseline fertilizer-to-crop price ratio ($R_{baseline}$=4.14).

The Impact of NUE Technologies on Yield

As agronomic research has shown, technologies like cultivar improvement, nitrification inhibitors, and slow-release fertilizers have improved NUE on a plot scale by achieving standard yields with less nitrogen fertilizer. However, few studies have reported how crop yields respond to additional nitrogen added to fields using the new technology after they have achieved standard yields. *Below et al.* (*2007*) proposed three potential ways that the NUE improvement technologies can change yield response curves (Table 2, Figure 3).

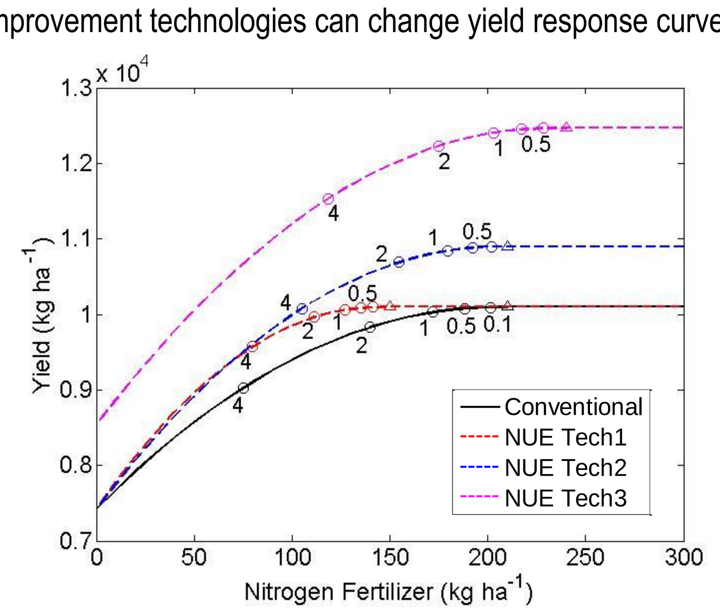

Figure 3 Three potential yield response changes from application of NUE improvement technologies. The solid line denotes the yield response under conventional technology. The dashed lines are yield responses under different NUE technologies. The triangle on each line is the yield ceiling (X_{max}, Y_{max}). The numbers indicate the relative change of the baseline fertilizer-to-crop price ratio. The circles on each line are the optimal nitrogen fertilizer rate ($X_{\pi max}$) under different fertilizer-to-crop price ratios. The nitrogen fertilizer rate is optimized to reach the maximum profit for farmers. NUE Tech 1 reaches the same yield ceiling as conventional technology with 30% less nitrogen fertilizer. NUE Tech 2 reaches a 10% higher yield ceiling at the same nitrogen fertilization rate as conventional technology. NUE Tech 3 reaches a 25% higher yield ceiling at higher fertilization rate.

Table 2 Three potential ways that the NUE improvement technologies can change the yield response curve.

	Yield response Scenario	Examples of available technology	Yield curve parameterization*
NUE Tech1	Standard yield ceiling with lower fertilization rate	Precision farming	$Y_{max,1} = Y_{max}$, $X_{max,1} < X_{max}$
NUE Tech2	Higher yield ceiling with standard fertilization rate	Controlled release fertilizer	$Y_{max,2} > Y_{max}$, $X_{max,2} = X_{max}$
NUE Tech3	Higher yields at all fertilization rates	Improved hybrid	$Y_{max,3} > Y_{max}$, $X_{max,3} > X_{max}$

*Assume the yield response for each technology follows quadratic-plus-plateau yield response relationship, but with different parameters.

$$Y_i = \begin{cases} a_i + b_i X + c_i X^2 & (X \le -b_i/2c_i) \\ -{b_i}^2/4c_i + a_i & (X > -b_i/2c_i) \end{cases}$$

The Impact of NUE Technologies on Nitrogen Application

Adopting NUE improvement technologies does not necessarily lead to a reduction of nitrogen application rates on the farm scale. Each NUE improvement technology has an optimal nitrogen application rate ($X_{\pi max,i}$) for famers to maximize their profit. As a result, the amount of nitrogen saved due to the adoption of a NUE improvement technology *i* can be calculated as $X_{\pi max,i} - X_{\pi max}$. $X_{\pi max}$ is the optimal nitrogen application rate under conventional technology. By adopting a NUE improvement technology, the resulting nitrogen saving linearly increases as the price of the new technology increases (Equation 8) under the following three basic assumptions 1) all additional costs of the NUE technologies are embedded in their fertilizer prices ($Pr_{fert,i}$); 2) corn prices are identical regardless of the NUE technology used in their production; and (3) there is no regulatory requirement to improve NUE and farmers decide nitrogen fertilization rates to maximize profits.

$$X_{\pi max,i} - X_{\pi max} = \frac{1}{2c_i Pr_{crop}} \cdot Pr_{fert,i} - \frac{b_i}{2c_i} + \frac{b}{2c} - \frac{1}{2c} \cdot \frac{Pr_{fert}}{Pr_{crop}} \quad (8)$$

When $Pr_{fert,i} < 2c_i Pr_{crop}\left(\frac{b_i}{2c_i} - \frac{b}{2c} + \frac{1}{2c} \cdot \frac{Pr_{fert}}{Pr_{crop}}\right)$, the adoption of the NUE technology will lead to a higher nitrogen fertilization rate. For example, when the fertilizer price of the NUE Tech 2 (NUE Tech 3) is less than 1.5 (2) times the baseline fertilizer price ($0.91 Nkg^{-1}) a higher fertilization rate will result (all the circles to the right of the vertical dashed line in Figure 4).

However, if $X_{max,i} < X_{\pi max}$ (or $-\frac{b_i}{2c_i} < -\frac{b}{2c} + \frac{1}{2c} \cdot \frac{Pr_{fert}}{Pr_{crop}}$), for example NUE Tech 1, the improved NUE technology would not increase nitrogen fertilization at any price.

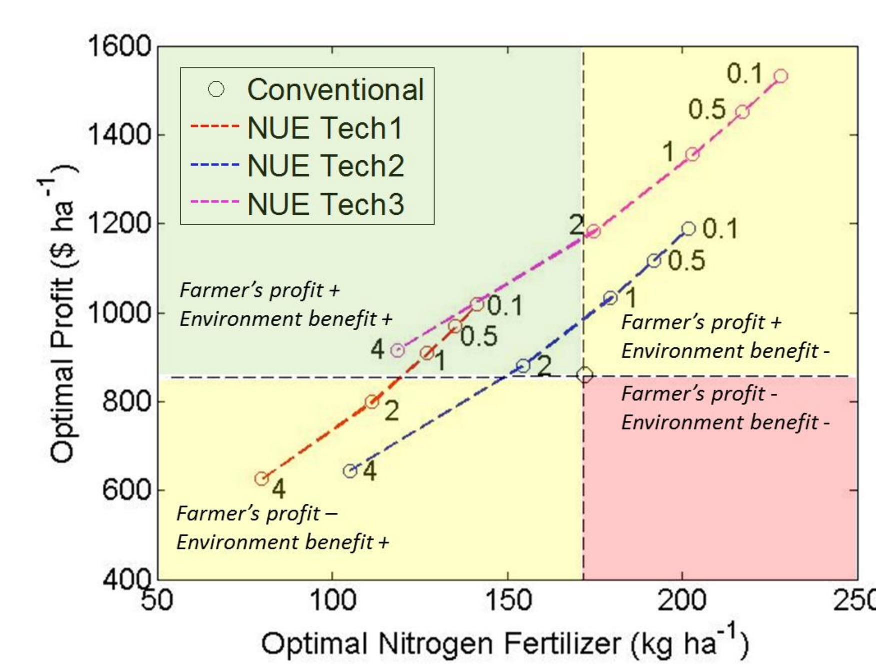

Figure 4. Optimal nitrogen fertilization rates and net profit for different technologies, under various fertilizer-to-crop price ratios. The black dashed lines denote the baseline scenario for the Conventional technology. The numbers in the graphs denote the relative change from the baseline fertilizer price ($0.91 kg N $^{-1}$).

The Impact of NUE Technologies on Profit and NUE

To encourage the adoption of NUE improvement technologies, farmer's profit after adopting NUE improvement technologies should be higher than before ($\pi_{\pi max,i} - \pi_{\pi max} > 0$). As a result, when $Pr_{fert,i} < \frac{2c}{b}\left[\left(a_i - \frac{{b_i}^2}{4c_i} - a + \frac{b^2}{4c}\right) Pr_{crop} + \frac{b_i}{2c_i} Pr_{fert,i}\right]$, the adoption of NUE improvement technology will increase farmer's profit (all the circles above the horizontal dashed line in Figure 4).

Given a NUE technology (for example, NUE Tech2 in Figure 5b), as the fertilizer price (or the technology price) decreases, farmer's profit increases, while nitrogen fertilizer application increases and NUE decreases. When the price decreases to certain level (the right edge of the blue box), the NUE Tech 2 becomes more profitable for farmers than conventional technology. As the technology price decreases further, applying NUE Tech2 becoming more attractive to farmers due to the increasing profit, however, it leads to less nitrogen savings and NUE improvement. When the price decreases to certain level (the left edge of the blue box), the application of NUE Tech2 will not achieve the environmental goal of reducing nitrous oxide emission through nitrogen input reduction.

For each NUE improvement technology, a price range can be estimated based on the change of yield response curve and baseline fertilizer and crop price in order to achieve both economic and environmental goals. When the price of a NUE improvement technology falls in the price range, the technology is likely to be adopted and will lead to reduction of nitrogen input. Government subsidies could reduce the NUE technology price into the price range . The wider the price range is, the easier for policy adjustment.

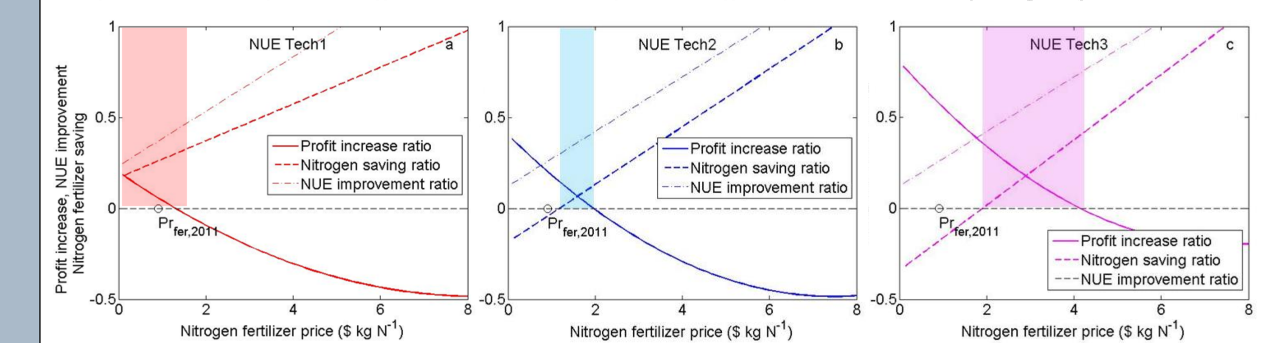

Figure 5. The impact of the price of NUE improvement technologies on farmer's profit, nitrogen fertilizer savings, and NUE improvement. The solid lines are the ratio of the profit increased by applying NUE improvement technology to the baseline profit achieved with conventional technology at the 2011 fertilizer and crop price. This is an indicator of the adoption rate of the technology. The red, blue, and magenta boxes demonstrate the price range for NUE Tech 1,2,3 respectively in order to ensure positive impact on farmer's profit and the environment.

Conclusions

1) When environmental conditions and nitrogen management technology remain the same, the nitrogen fertilization rate maximizing farmer's profit is determined by the price ratio of nitrogen fertilizer to crop product. Fertilizer price increases will lead to less nitrogen application, higher nitrogen use efficiency, and lower nitrous oxide emission, but will lead to yield and profit reduction for farmers. Crop price increases have the opposite impact.

2) The adoption of a NUE improvement technology does not necessarily lead to reduction of nitrous oxide emissions. To reduce the nitrogen application rate while encouraging adoption of NUE technology, the price of the technology should lie within a certain range. The range is determined by how the technology changes the yield response curve and the baseline fertilizer and crop prices.

3) Technologies (e.g. NUE Tech1) that reach the same yield ceiling at much lower fertilization rates would not increase nitrogen application rates, however, the cost of the technology must be close to the conventional technology price for the technology to be adopted. Technologies (e.g. NUE Tech2, 3) that have higher yield ceilings can potentially increase nitrogen application rates when the technology price is low.

4) Our model can evaluate the effectiveness of NUE technologies in reducing regional nitrogen fertilization. It can provide guidance on how to subsidize or price NUE technologies to meet mitigation targets for reactive nitrogen application and nitrous oxide emissions.

Key References

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Contact information

Xin ZHANG
Postdoctoral Research Associate,
Program in Science, Technology and Environmental Policy
Woodrow Wilson School of Public and International Affairs, Princeton University

R413A, Robertson Hall
Princeton, NJ, 08544

Tel. (O): 609.2581876
Email: xz2@priceton.edu