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IMPROVING NITROGEN USE EFFICIENCY IN CROP AND LIVESTOCK PRODUCTION SYSTEMS

The Economic and Environmental Consequences of Implementing Nitrogen-Efficient Technologies and Management Practices in Agriculture

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Abstract

Technologies and management practices (TMPs) that reduce the application of nitrogen (N) fertilizer while maintaining crop yields can improve N use efficiency (NUE) and are important tools for meeting the dual challenges of increasing food production and reducing N pollution. However, because farmers operate to maximize their profits, incentives to implement TMPs are limited, and TMP implementation will not always reduce N pollution. Therefore, we have developed the NUE Economic and Environmental impact analytical framework (NUE^3) to examine the economic and environmental consequences of implementing TMPs in agriculture, with a specific focus on farmer profits, N fertilizer consumption, N losses, and cropland demand. Our analytical analyses show that impact of TMPs on farmers' economic decision-making and the environment is affected by how TMPs change the yield ceiling and the N fertilization rate at the ceiling and by how the prices of TMPs, fertilizer, and crops vary. Technologies and management practices that increase the yield ceiling appear to create a greater economic incentive for farmers than TMPs that do not but may result in higher N application rates and excess N losses. Nevertheless, the negative environmental impacts of certain TMPs could be avoided if their price stays within a range determined by TMP yield response, fertilizer price, and crop price. We use a case study on corn production in the midwestern United States to demonstrate how NUE^3 can be applied to farmers' economic decision-making and policy analysis. Our NUE^3 framework provides an important tool for policymakers to understand how combinations of fertilizer, crop, and TMP prices affect the possibility of achieving win-win outcomes for farmers and the environment.

Improving nitrogen use efficiency (NUE) in crop production worldwide has been proposed as a strategy for meeting food demand, slowing environmental degradation, and mitigating climate change (Cassman et al., 2003; Davidson, 2012; Foley et al., 2011; Johnson et al., 2007; Tilman et al., 2011; UNEP, 2013). Although nitrogen (N) fertilizer is critical in boosting crop yields and in reducing pressure to expand land under cultivation, it has profound environmental impacts. The production of N fertilizer is an energy-intensive process (Grassini et al., 2011; Zhang et al., 2013), and its use frequently leads to reactive N losses, including nitrate leaching, ammonia volatilization, and nitrous oxide emissions, which affect water quality, air quality, ozone layer depletion, and climate change (Galloway et al., 2003; Ravishankara et al., 2009; Reay et al., 2012). In practical terms, NUE improvement means that more food is produced with less N fertilizer, reducing environmental impacts as a result (Fageria and Baligar, 2005). As agronomic research has shown, technologies and management practices (TMPs), such as cultivar improvement, precision fertilizer application, nitrification inhibitors, and controlled-release fertilizers, can improve NUE at the farm scale by achieving standard yields using less N fertilizer (Akiyama et al., 2010; IFA, 2007). Consequently, implementing TMPs is crucial for improving NUE and reducing N pollution (Fageria and Baligar, 2005). Technologies and management practices are different from best management practices (BMPs) in that inputs are optimized in BMPs to reach production and environmental targets, whereas only some TMPs could qualify as optimized BMPs.

Although more TMPs have become available and affordable and NUE has increased in some regions, NUE has stagnated globally and has even decreased in many developed and developing countries in recent decades (Cassman et al., 2003). Coupled with increasing N fertilizer consumption, this has led to increasing levels of N pollution (Conant et al., 2013). The apparent discrepancy between the increasing availability of

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Abbreviations: BMPs, best management practices; ESN, Environmentally Smart Nitrogen; NUE, nitrogen use efficiency; PA, planting area; TMPs, technologies and management practices.

more efficient technologies and increasing levels of N pollution indicates that TMP effectiveness, availability, and price are not the only factors that determine N pollution but that other economic factors, such as fertilizer and crop prices, need to be taken into account (Knapp and Schwabe, 2008; Larson et al., 1996; Preckel et al., 2000; Sheriff, 2005; Sylvester-Bradley and Kindred, 2009). Consequently, to investigate how implementing TMPs affects the environmental impact of crop production, including N fertilizer consumption, N losses, and cropland demand, we need to consider two additional elements: (i) how TMPs change the yield response to N inputs and (ii) how changing prices for TMP, fertilizer, and crops affect yields, N application rates, resulting NUE, and excess N loss to the environment.

To date, several models have been developed that characterize yield response to N input to provide preplanting, in-season, or postseason recommendations on N application rates (Fageria and Baligar, 2005; Janssen et al., 1990; Setiyono et al., 2011; Yang et al., 2004). Most process-based and empirical models suggest that as the yield level approaches its potential, there is a decreasing yield response to additional N application. This relationship has been described using various forms of yield response functions, including spherical-plateau, exponential, and quadratic-plateau (Jaynes, 2011), with the latter often being used to determine economically optimal N fertilization rates (Cerrato and Blackmer, 1990; Hong et al., 2007; Sawyer et al., 2006; Yadav et al., 1997). In the United States and Europe, the yield response curve and the fertilizer-crop price ratio are commonly used to provide recommendations to farmers on optimal N application rates (Sawyer et al., 2006; Sylvester-Bradley and Kindred, 2009).

Studies in agricultural economics are increasingly using nonlinear yield responses characterized by field experiments or biological models to investigate farmer decisions regarding N inputs and how these decisions are affected by risk factors and policies, such as N taxes and crop insurance (Horowitz and Lichtenberg, 1993; Huang and LeBlanc, 1994; Larson et al., 1996; Isik and Khanna, 2003; Sheriff, 2005; Knapp and Schwabe, 2008). Several recent studies integrate biological and economic dynamics into a single model to better characterize temporal and spatial heterogeneity of yield responses and to provide a better evaluation on the effect of a N tax (Isik and Khanna, 2003; Knapp and Schwabe, 2008; Mérel et al., 2014). However, few studies have considered the impact of more efficient technologies and management practices on yield response. In addition, many studies focus solely on the nitrate pollution in water when considering the environmental impacts of excess N use instead of an integrated assessment of reactive N's environmental impacts throughout the N cascade. A detailed literature review on this subject is included in the supplementary materials.

Here we present a new analytical framework based on yield response curves and profit maximization objectives to investigate the impact of TMP implementation on farmer profits and the environment, including N fertilizer consumption, N losses, and cropland demand. Taking such a broad view is critical for evaluating the likelihood of farmer adoption of TMPs and their resulting environmental consequences. In turn, using a case study of corn production in the midwestern United States, we demonstrate the impact of implementing TMPs on economic and environmental outcomes and how such impacts could be affected by TMP price, fertilizer price, and crop price. Then, using analytical approaches, we examine whether the findings on a single farm could be relevant to the heterogeneous conditions found at the regional scale. We conclude by examining the policy implications of implementing TMPs that attempt to achieve environmental goals.

Materials and Methods

Description of the NUE^3 Framework

Our framework includes three components (Fig. 1): (i) a yield response module, using a quadratic-plateau yield response function to characterize yield response to N application; (ii) an optimization module, optimizing the N application rate for maximizing farmer profits based on a cost-benefit analysis; and (iii) an evaluation module, comparing and evaluating the impact of TMP implementation on farmer profits and the environment (including N application rate, excess N, and potential demand for cropland).

Yield Response Module

Crop yield is affected by many factors, including climate and soil conditions, management practices, and nutrient input. Among these factors, insufficient N can significantly limit yield, especially when the soil N supply is already low (Cassman et al., 2003). Therefore, we consider yield (Y) as a function of N application rate (X), which includes N inputs through fertilizer, manure, and biological fixation. For a farm without manure application and N fixing crops, the N application rate is the same as the N fertilization rate. The format of the function is a quadratic-plateau yield response relationship, which is commonly

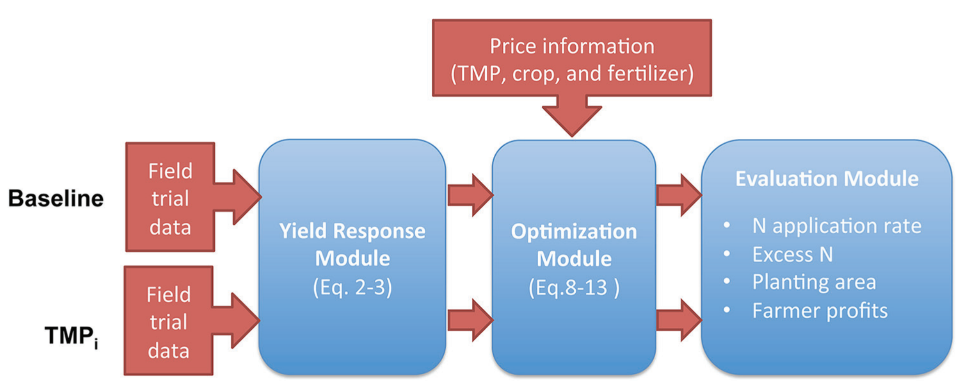

Fig. 1. Flow chart of the Nitrogen Use Efficiency Economic and Environmental Impact Analytical (NUE^3) framework. Blue boxes are the three major framework modules. Red boxes indicate the major inputs. TMP, technologies and management practice.

used to determine optimal N application rates (Cerrato and Blackmer, 1990; Sawyer et al., 2006)

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

where a, b, and c are coefficients of the yield response curve, with $a > 0$, $b > 0$, and $c < 0$. The coefficients can be determined by fitting yield and N application data to the function for crops grown using the same management practices. Uncertainties in the parameter estimation can be attributed to year-to-year variation in weather and/or heterogeneity of the soil. The yield response function can also be written with the following more intuitive parameters:

$$Y=\begin{cases} Y_0+\dfrac{2(Y_{\max}-Y_0)}{X_{\max}}X-\dfrac{(Y_{\max}-Y_0)}{X_{\max}{}^2}X^2 & (X\le X_{\max}) \\ Y_{\max} & (X>X_{\max}) \end{cases} \quad [2]$$

where Y_0 is the yield level without N application ($X_0 = 0$), Y_{max} is the maximum potential yield, and X_{max} is the N application rate when the yield first reaches the yield ceiling (the maximum yield). In addition, $Y_{max} > Y_0 > 0$ and $X_{max} > 0$.

Nitrogen use efficiency has been defined in many ways in the literature (Fageria and Baligar, 2005), and in this study we will use two different definitions to calculate NUE. One is apparent N recovery efficiency (NUE_r, measured in kg N harvested kg^{-1} N applied; Eq. [3]), which is the percentage of N fertilizer applied that is recovered in the harvested crop, and the other is the partial factor productivity of applied N (NUE_p, measured in kg grain yield kg^{-1} N applied; Eq. [4]), which is the ratio of crop yield to N fertilizer applied:

$$\mathrm{NUE_r}=\frac{(Y-Y_0)\cdot \mathrm{NC}}{X} \quad [3]$$

$$\mathrm{NUE_p}=\frac{Y}{X} \quad [4]$$

where NC is the N content of the crop (kg N per kg crop product) (Bouwman et al., 2005). We use both of these NUE definitions here because ($1 - NUE_r$) is a good indicator of N lost to the environment, and NUE_p is a direct measure of yield response to N input. The NUE_p data are more available on both farm and global scales.

To evaluate the impact of TMPs on the environment, we use three indicators. (i) The N application rate (X). The application rate is examined because the production of N fertilizer is a very energy-intensive process, and fertilizer is a major energy input for crop production (Grassini et al., 2011; Zhang et al., 2013). (ii) Planting area (PA) needed for a given production level. The implementation of some TMPs may result in higher yield levels, which would lead to external environmental benefits, such as reduce the demand for conversion of native vegetation to extensive (low productivity) forms of agriculture. To evaluate TMPs' land-sparing benefits, we calculate the relative change of cropland demand after implementing TMPs, given the same production goal (P). As a result, the planting area needed to reach a production level (P) can be written as PA = P/Y. (iii) Excess N (N_{exc}). We define excess N as the N applied to cropland that is not taken up by crops (Eq. [5]) and assume it is lost to the environment in a variety of forms, with negative environmental impacts occurring along the N cascade (Galloway et al., 2003).

$$\mathrm{N_{exc}}=(1-\mathrm{NUE_r})\cdot X \quad [5]$$

Nitrogen dynamics in soil is very complex, involving processes such as plant uptake, immobilization, mineralization, nitrification, denitrification, and leaching. Nitrogen left in the environment may accumulate as soil N, but we assume that, over the long term, the changing rate of soil N stock is negligible compared with the N input, including fertilizer, biological fixation, manure, and deposition (Bouwman et al., 2005; Cherry et al., 2008; Oenema et al., 2003; Sheldrick et al., 2002).

Efforts to monetize the environmental costs of N pollution are relatively new and must be considered preliminary (Birch et al., 2011; Brink et al., 2011; Compton et al., 2011; Gu et al., 2012). Nevertheless, as an initial effort to put environmental costs into perspective with profits, we assume that the environmental cost (EC) of N fertilizer application can be estimated by the amount of N lost in each of the four reactive N forms (j: N_2O, NO_3^-, NO_x, NH_3) and the resulting damage costs (DC_j) to human health (e.g., adverse consequences of nitrate water pollution and air pollution resulting from fine particulate and ozone pollution from NO_3^-, NO_x, and NH_3 emissions) and the environment (e.g., increased climate change from N_2O emissions and losses of biodiversity and ecosystem services from eutrophication of changing flora due to excess NO_3^-) (Brink et al., 2011; Compton et al., 2011; Gu et al., 2012). The environmental costs (EC) are:

$$\mathrm{EC}=\sum_j \mathrm{N_{exc}}\cdot \mathrm{Frac}_j\cdot \mathrm{DC}_j \quad [6]$$

where $Frac_j$ is the fraction of N_{exc} released to the environment in each reactive N form. We use the IPCC emission factors (EF_j in Table 1) to estimate the partitioning between reactive N forms and in this framework assume the fraction of each form of reactive N stays the same across fields and crops ($\mathrm{Frac}_j = EF_j/\sum_j \mathrm{EF}_j$). Nevertheless, the proportion of each reactive N form lost to the environment may differ greatly between regions due to the climate and soil conditions and management practices, and more studies are needed to better understand the heterogeneity of the N lost in different forms.

Optimization Module: Cost-Benefit Analysis and N Application Rate

Farmers typically seek to maximize profit by optimizing their N application rate and management practices. To investigate a farmer's decision regarding N fertilizer rate in the context of different management practices, we define farmer profits (π in Eq. [7]) as the difference between revenues from crop production and the costs of N fertilizer and other operating costs ($Cost_{other}$) (USDA–ERS, 2013).

$$\pi = A\cdot(Y\cdot \mathrm{Pr_{crop}}-X\cdot \mathrm{Pr_{fert}}-\mathrm{Cost_{other}}) \quad [7]$$

where Pr_{crop} and Pr_{fert} are the prices of the crop sold and the N fertilizer applied per hectare, respectively, and A is farm size in hectares.

Assuming farmers adjust their N application rates to maximize their net profit (π), the optimal N application rate (X^*) can be derived from Eq. [2] and [7] based on the concept that marginal revenue equals marginal cost when profit is maximized.

$$X^* = X_{max}\left[1 - \frac{R \cdot X_{max}}{2(Y_{max} - Y_0)}\right] \quad [8]$$

where R is the fertilizer-to-crop price ratio (Pr_{fert}/Pr_{crop}). The corresponding profit maximizing yield (Y^*), net profit (π^*), NUE (NUE_r^* and NUE_p^*), and excess N ($N_{exc,\pi max}$) are:

$$Y^* = Y_{max} - \frac{R^2 \cdot X_{max}^2}{4(Y_{max} - Y_0)} \quad [9]$$

$$\pi^* = A\left[\frac{Pr_{fert}^2 \cdot X_{max}^2}{4(Y_{max} - Y_0)Pr_{crop}} - Pr_{fert} \cdot X_{max} - Cost_{other} + Pr_{crop} \cdot Y_{max}\right] \quad [10]$$

$$NUE_r^* = NC\left[\frac{Y_{max} - Y_0}{X_{max}} + \frac{R}{2}\right] \quad [11]$$

$$NUE_p^* = \frac{R^2 \cdot X_{max}^2 - 4Y_{max}^2 + 4Y_0 Y_{max}}{4X_{max}(Y_0 - Y_{max}) + 2R \cdot X_{max}^2} \quad [12]$$

$$N_{exc}^* = \frac{(2Y_0 - 2Y_{max} + R \cdot X_{max}) \cdot (2X_{max} + 2NC \cdot Y_0 - 2NC \cdot Y_{max} - NC \cdot R \cdot X_{max})}{4(Y_0 - Y_{max})} \quad [13]$$

As a result, if the production function remains constant for a given farm (i.e., if Y_0, Y_{max}, and X_{max} in the yield response function do not change), then when the fertilizer-to-crop price ratio (R) increases, N application rates decrease to maximize farmer profits according to Eq. [8]. Consequently, NUE_r^* and P/Y^* increase, whereas Y^* and N_{exc}^* decrease (according to Eq. [5], [9], [11], and [13]). The impact of an increase in R on profit is more complex. By examining Eq. [8] and [10], we find that as long as $X^* \geq 0$, the maximum profit (π^*) decreases as fertilizer price increases or crop price decreases.

Evaluation Module: Technologies and Management Practices Impact on Farmer Profits and the Environment

Based on field studies on the yield response with and without implementing a TMP_i, we can derive two yield response functions using the Yield Response Module (Fig. 1). Then, with the price information for the TMP_i, crop, and fertilizer, the optimized N fertilizer application rate and resulting excess N, planting area, and farmer profits can be calculated for a farm with (X_i^*, $N_{exc,i}^*$, PA_i^*, π_i^*) and without the implementation of a TMP_i (X^*, N_{exc}^*, PA^*, π^*). Details about parameters can be found in the supplementary materials. The impact of a TMP on farmer profits and the environment can therefore be evaluated by $d\pi^* = \pi_i^* - \pi^*$, $dX^* = X_i^* - X^*$, $dN_{exc}^* = N_{exc,i}^* - N_{exc}^*$, and $dPA^* = PA_i^* - PA^*$, where $d\pi^* > 0$, $dX^* < 0$, $dN_{exc}^* < 0$, and $dPA^* < 0$, indicating that implementing a TMP has a positive impact on farmer profits and all environmental parameters. The signs of these factors are determined by the shape of the production functions and by the price of the fertilizer, crop, and TMP.

Case Study for Midwestern U.S. Corn Production

We show here how our framework can be applied to investigate the economic and environmental consequences of implementing TMPs. We examine the implementation of three different TMPs on corn, using a yield response function for corn in the midwestern United States, and examine how farmer profits and various environmental parameters change under different price scenarios. In addition, we repeat the analysis for several other yield response functions in the literature to test the sensitivity of our results to the shape of the yield response curve.

Due to different regional soil and climate conditions, the corn yield response to N application varies significantly (Below et al., 2007; Below et al., 2009; Boyer et al., 2013; Cerrato and Blackmer, 1990; Gentry et al., 2013; Haegele and Below, 2013; Sawyer et al., 2006; Setiyono et al., 2011; Yadav et al., 1997). We first use the yield response function in Below et al. (2007) as the baseline function in the NUE[3] framework because it was derived from 37 on-farm studies across five midwestern states (Indiana, Illinois, Iowa, Minnesota, and North Dakota) (Below et al., 2007; Gentry et al., 2013; Haegele and Below, 2013) and lies approximately in the middle of reported yield response functions. Baseline crop and fertilizer prices and farmer's costs were determined by statistics for corn production in the United States (Table 2) (USDA–ERS, 2013).

Numerous studies show how TMPs affect corn yield response to N input (Blaylock et al., 2005; Ciampitti and Vyn, 2012; Fageria and Baligar, 2005; Gehl et al., 2005; Sylvester-Bradley and Kindred, 2009). Implementing TMPs can change yield response curves in three ways (Table 3), (Below et al., 2007; Cassman et al., 2003): TMP1 achieves the standard yield ceiling ($Y_{max,1} = Y_{max}$) at a lower N application rate ($X_{max,1} < X_{max}$), TMP2

Table 1. Emission factors and damage costs of four forms of reactive N.

Reactive N species	IPCC emission factor (De Klein et al., 2006)	Fraction of N_{exc}† emitted as reactive N species	Damage cost estimation 2005 \$ kg N^{-1}‡
N_2O	0.013§	0.03	8.2 (2.3–30.3)
NO_3^-	0.3	0.73	39.4 (8.4–57.2)
NO_x	0.05	0.12	24.6 (15.7–67.4)
NH_3	0.05	0.12	13.7 (1.1–50.6)

† Excess N.

‡ We averaged the estimation of the damage cost from Compton et al. (2011), Brink et al. (2011), and Gu et al. (2012). The values in parentheses are the largest and smallest values of all studies above (Kanter et al., 2014).

§ This includes direct and indirect emissions from N application to cropland.

Table 2. Case study: Input data summary.

Parameter†	Value	Data source
Pr_{crop}	\$0.22 kg $^{-1}$	corn price for U.S. heartland‡ in 2011 (USDA ERS, 2013)
Pr_{fert}	\$0.91 kg N $^{-1}$	anhydrous ammonia price for U.S. in 2011 (USDA ERS, 2013)
$Cost_{other}$	\$1189 ha^{-1}	total cost minus fertilizer cost for corn farm in U.S. heartland in 2011 (USDA–ERS, 2013)
Y_0	6931 kg ha^{-1}	Below et al., 2007
X_{max}	146 kg N ha^{-1}	Below et al., 2007
Y_{max}	10,707 kg ha^{-1}	Below et al., 2007

† $Cost_{other}$, other operating costs; Pr_{crop}, price of crop sold; Pr_{fert}, price of the N fertilizer applied per hectare; X_{max}, N application rate when the yield first reaches the yield ceiling (the maximum yield); Y_{max}, maximum potential yield; Y_0, yield level without N application.

‡ Heartland is the 12 states in the United States, including Wisconsin, Indiana, Illinois, Minnesota, Michigan, Kansas, Iowa, North Dakota, Nebraska, Ohio, South Dakota, and Missouri. See the supplementary information for a sensitivity analysis of these parameterizations and the range of values reported in the literature.

reaches a higher yield ceiling ($Y_{max,2} > Y_{max}$) at the same or lower application rate ($X_{max,2} \leq X_{max}$), and TMP3 reaches a higher yield ceiling ($Y_{max,3} > Y_{max}$) at a higher application rate ($X_{max,3} > X_{max}$).

The yield responses for the these TMP examples are reported in different formats and with different baselines. As an example of TMP1, Gehl et al. (2005) examined the field trial data at a variety of locations in Kansas and concluded that in irrigated soils side dressing can reach the same yield level as soils without side dressing but with 40% less N fertilizer. An example of TMP2 is the change in yield response functions with and without the use of Environmentally Smart Nitrogen (ESN, a controlled-release N fertilizer) derived from extensive field experiments in the U.S. corn belt (Blaylock et al., 2005; Blaylock, 2013; Nelson and Motavalli, 2008). An example of TMP3 is reported by Ciampitti and Vyn (2012), who characterize the change in yield curves resulting from improved crop cultivars. They examined the yield response function of corn hybrids in the "Old Era" (1940–1990) and "New Era" (1991–2011) based on field trials documented in the literature. Similar further improvements could be made as still newer hybrids are developed to replace those widely adopted since 1991. These three examples are not meant to be representative of all TMPs but rather to demonstrate the value of an analytical framework for understanding how technologies and management practices can affect yields and cost-price ratios in multiple ways.

To synthesize results from the literature and to compare the impact of TMPs on yield response, we normalize all yield response functions by the minimum and maximum yield levels and the corresponding N application rate without applying TMP_i:

$$\left(Y_i' = \frac{Y_i - Y_0}{Y_{max} - Y_0}, X_i' = \frac{X_i}{X_{max}} \right)$$

As a result, the normalized yield response function is:

$$Y_1' = \begin{cases} A_i + B_i X_i' + C_i X_i'^2 & (X_i' \leq -B_i/2C_i) \\ -B_i^2/4C_i + A_i & (X_i' > -B_i/2C_i) \end{cases}$$

Table 3. Technologies and management practices yield response scenarios.

TMP†	Yield response scenario	Examples of available technology	Yield curve parameterization‡	Case study§
TMP1	standard yield ceiling with lower N application rate	precision farming (Dobermann et al., 2004; Gehl et al., 2005); improved hybrid (Below et al., 2007; Sylvester-Bradley and Kindred, 2009; Haegele and Below, 2013);	$Y_{max,1} = Y_{max}$ $X_{max,1} < X_{max}$	$Y_1' = \begin{cases} 0 + 3.33X' - 2.78X' & (X' \leq 0.60) \\ 1 & (X' > 0.60) \end{cases}$ side dressing (Gehl et al., 2005)
TMP2	higher yield ceiling with standard or lower N application rate	controlled release fertilizer (Blaylock, 2013); precision farming (Cassman et al., 2003; Godwin et al., 2003); improved hybrid (Below et al., 2007); soil management (Halvorson et al., 2006)	$Y_{max,2} > Y_{max}$ $X_{max,2} \leq X_{max}$	$Y_2' = \begin{cases} 0 + 2.48X' - 1.32X'^2 & (X' \leq 0.93) \\ 1.15 & (X' > 0.93) \end{cases}$ Environmentally Smart Nitrogen (Blaylock, 2013)
TMP3	higher yields at higher N application rates	improved hybrid (Below et al., 2007; Ciampitti and Vyn, 2012; Haegele and Below, 2013)	$Y_{max,3} > Y_{max}$ $X_{max,3} > X_{max}$	$Y_3' = \begin{cases} 0.13 + 2.27X' - 0.94X'^2 & (X' \leq 1.20) \\ 1.50 & (X' > 1.20) \end{cases}$ improved hybrid (Ciampitti and Vyn, 2012)

† Technologies and management practice (TMP1, side dressing; TMP2, Environmentally Smart Nitrogen; and TMP3, improved hybrid).

‡ Assume the yield ceiling and the corresponding N application rate for each technology are $Y_{max,i}$ and $X_{max,i}$, respectively.

§ The yield response function in this column is normalized by the minimum yield level (Y_0), maximum yield level (Y_{max}), and the corresponding N applicaiton rate (X_{max}) before implementing a TMP. Y_i' and X_i' are defined as $Y_i' = (Y_i - Y_0)/(Y_{max} - Y_0)$ and $X_i' = X_i/X_{max}$. Please refer to the supplementary information for a detailed definition of each parameter.

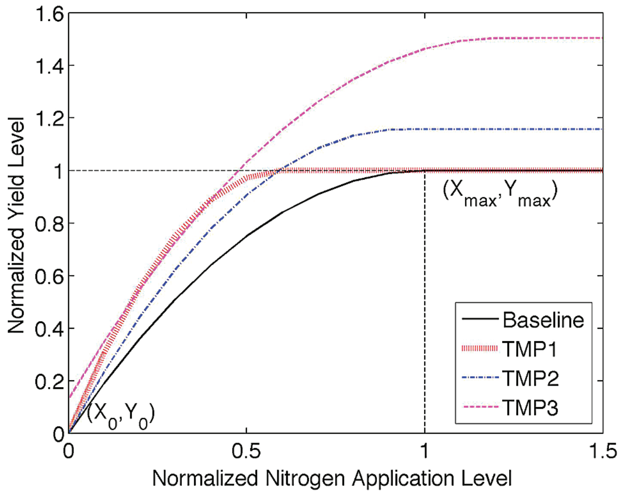

Fig. 2. Relative changes of yield response to fertilizer application after implementing technologies and management practices (TMPs). The black solid line denotes the baseline scenario. The dotted line, dash-dotted line, and the dashed line are the yield responses when TMP1 (e.g., side dressing), TMP2 (e.g., ESN), and TMP3 (e.g., improved hybrid), respectively, are used. The (0,0) and (1,1) points correspond to (X_0, Y_0) and (X_{max}, Y_{max}) in the yield response function before implementation of TMPs, where *Y* is yield as a function of N application rate (*X*).

where A_i, B_i, and C_i are the parameters for the normalized yield response function. Figure 2 and Table 3 show the normalized yield response curves from Gehl et al. (2005) (side dressing), Blaylock (2013) (ESN), and Ciampitti and Vyn (2012) (improved hybrids) using the process described above. The three normalized yield response curves demonstrate three examples of how TMPs can improve the baseline yield response described in Table 3.

The yield response function after applying each TMP was derived according to the baseline yield response function and normalized impact of each TMP. This derivation is based on the assumption that the mathematical formulations of TMPs in the fifth column in Table 3 can be applied to other farms in the midwestern United States, although the parameters may change based on local circumstances. The resulting yield response functions are used as input in the following analysis.

Results and Discussion

Case Study Results

Economic and Environmental Impact of Fertilizer and Crop Prices

To explore the economic and environmental impact of fertilizer and crop prices, we use as an example the fertilizer-to-corn price ratio in 2011 for a farm having the same production function as Below et al. (2007). We found the economically optimal N application rate for maximizing farmer profits, according to Eq. [8–13], to be 134 kg N ha^{-1}. The resulting NUE_r and excess N were 0.39 and 82 kg N ha^{-1}, respectively.

Given the same farm and same N management practices, the economically optimal N application rate declines if the fertilizer-to-corn price ratio increases due to an increase in fertilizer price (Fig. 3a). As a result, farmer profits decrease (Fig. 3a), NUE_r improves (Fig. 3b), excess N loss decreases (Fig. 3c), and demand for PA increases. Similarly, the same increase in the fertilizer-to-corn price ratio caused by a decreasing corn price also leads to the same reduction in N application rate and excess N and the same improvement in NUE but to a much steeper decrease in farmer profits.

The impact of fertilizer and crop prices on economic (farmer profits), environmental (N application rate, excess N, PA), and efficiency (NUE_r and NUE_p) outcomes follows the same trends in farms that do and do not implement a TMP (Fig. 4–6).

Economic and Environmental Impact of Technologies and Management Practices Implementation

The impact of TMP implementation on farmer profits and the environment is closely related to TMP costs, which are defined as costs added to the previous farming operations solely due to implementing the TMP. There are two pricing schemes for our TMP cases. (i) The TMP cost is independent of the N

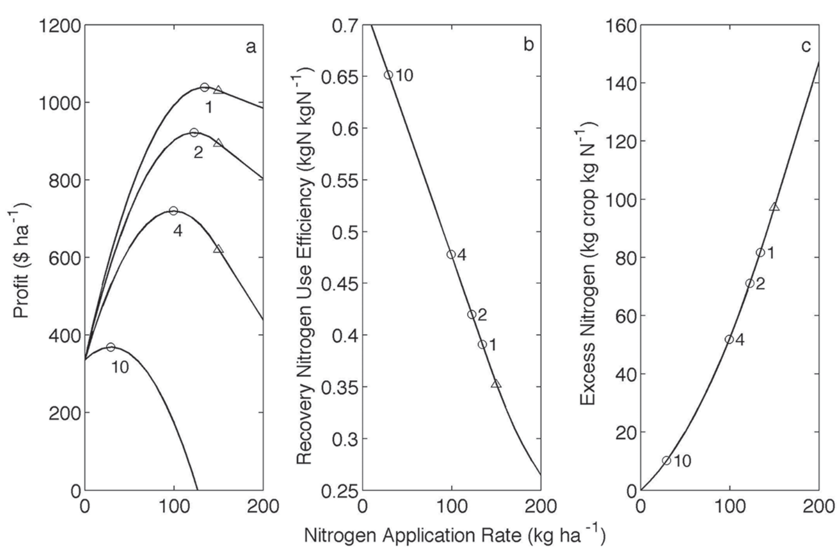

Fig. 3. Response of (a) farmer's net profits to fertilizer price changes and resulting (b) recovery efficiency and (c) excess N. The circles denote optimized N application rates that maximize the farmer's profit under specific fertilizer and crop prices. The numbers beside the circles indicate the fertilizer price scenario: 1 is the baseline scenario for the midwestern United States in 2011 when fertilizer price is $0.91 kg N^{-1} and the fertilizer-to-crop price ratio (*R*) is 4.14; 2, 4, and 10 indicate multiples of fertilizer price. The triangles indicate the N application rate when yields reach the yield ceiling.

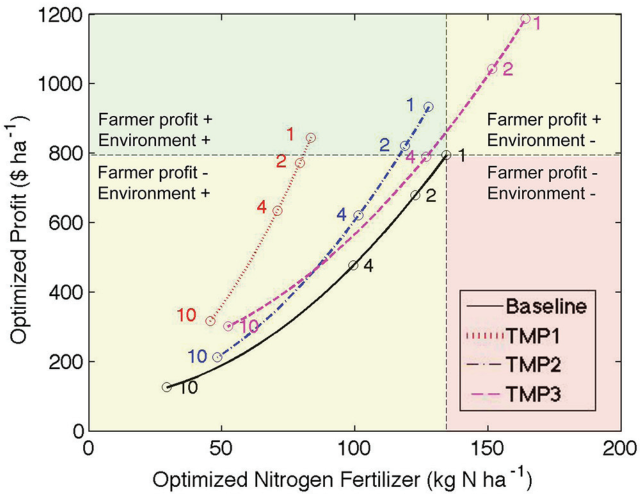

Fig. 4. Optimized N application rates and profit for different technologies under various fertilizer price scenarios. The black solid line denotes the optimized N rate and profit for a farm before implementing technologies and management practices (TMPs). The red dotted line, blue dash-dotted line, and the magenta dashed line are the optimized N rate and profit for a farm implementing TMP1 (side dressing), TMP2 (Environmentally Smart Nitrogen), and TMP3 (improved hybrid). The numbers in the graphs denote the relative change from the baseline fertilizer price (0.91 \$ kg N^{-1}). For example, the number 2 means the fertilizer (or fertilizer and technology) price increases to twice the baseline fertilizer price.

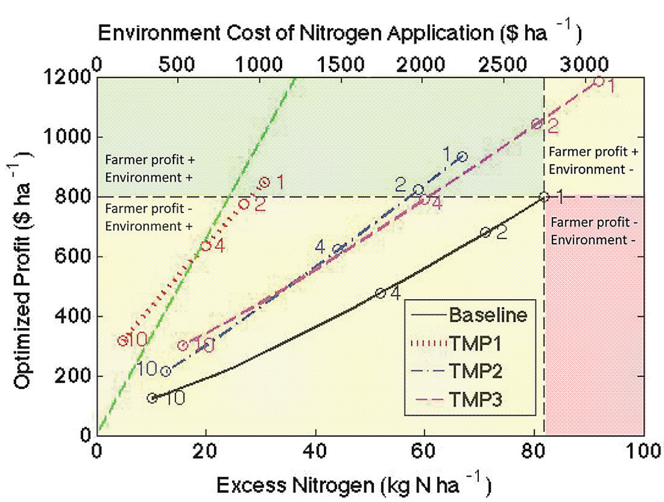

Fig. 5. Optimized profit and resulting excess N and environment costs for different technologies and management practices under various fertilizer price scenarios. The green dashed line denotes where farmer profits equal the environmental cost (calculated according to the averaged damage cost in Table 1). TMP, technologies and management practice (TMP1, side dressing; TMP2, Environmentally Smart Nitrogen; and TMP3, improved hybrid).

application rate (e.g., side dressing and improved hybrids are usually priced as \$ ha^{-1}). Therefore, farmer profits in Eq. [7] become $\pi = A \cdot [Y \cdot Pr_{crop} - X \cdot Pr_{fert} - (Cost_{other} + Pr_{TMP,i})]$, where $Pr_{TMP,i}$ is the price of TMP_i; and (ii) the TMP cost depends on the N application rate (e.g., ESN is usually priced as \$ kg N^{-1}). Therefore, farmer profits become $\pi = A \cdot [Y \cdot Pr_{crop} - X \cdot (Pr_{fert} + Pr_{TMP,i} - Cost_{other})]$. In the following two sections, we examine the economic and environmental impact of implementing each TMP case under \$ ha^{-1} and \$ kg N^{-1} price schemes.

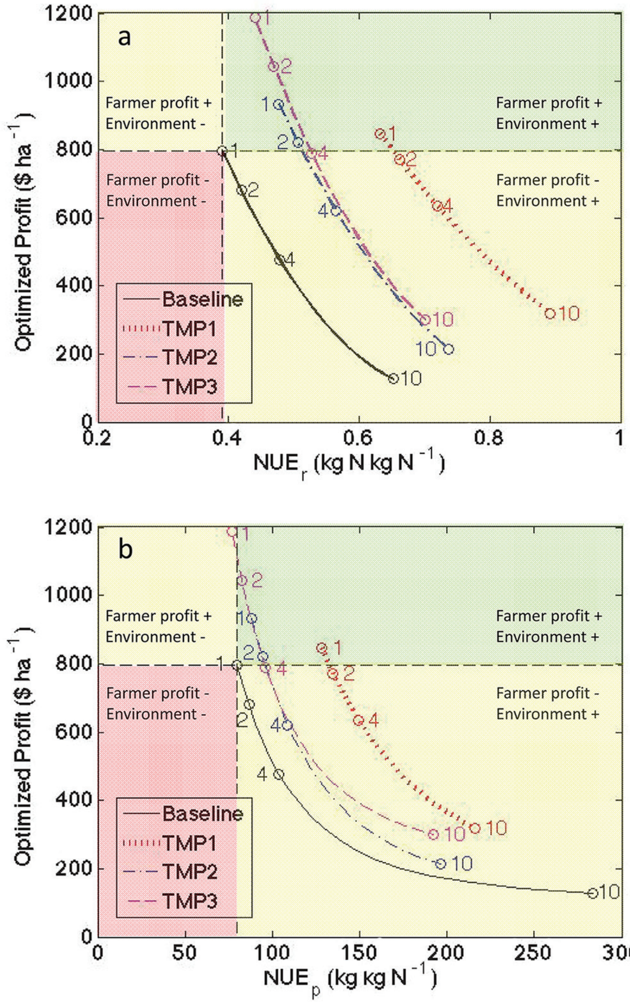

Fig. 6. Optimized profit and resulting N use efficiency (NUE) for different technologies and management practices (TMPs) under various fertilizer-to-crop price ratios. The NUE$_r$ (a) is apparent N recovery efficiency, and the NUE$_p$ (b) is partial factor productivity of applied N.

Economic and Environmental Impact of Technologies and Management Practices Priced as \$ ha^{-1}

When TMPs are priced as \$ ha^{-1}, the optimized N application rate for each TMP is not affected by TMP price and is determined by the new yield response function and the baseline fertilizer and crop price scenario (the circles noted with number 1 in Fig. 4). The horizontal distance between the circle labeled with "1" for each TMP and the vertical dotted line denotes the TMP's impact on N application rate. Among the three cases we investigated, only side dressing leads to a significant reduction in N application rate (38%); ESN reduces the N rate by only 5%, and the use of improved hybrids increases the N rate by 22%.

Similarly, the implementation of side dressing and ESN reduces excess N by 63 and 18%, respectively, whereas improved hybrids increase excess N by 12% (Fig. 5; compare the circles labeled "1" for the TMPs relative to the base case).

In contrast, implementing improved hybrids increases the yield. Therefore, 15% less land is required to meet the same production demand. Side dressing has a negligible impact on land sparing, whereas ESN may reduce cropland demand by 5% for the same total crop production.

The potential profit increase by implementing a TMP is the vertical distance between the circle labeled with "1" and the horizontal dotted line. In this example, TMP implementation can increase farmer profits only when their costs are lower than 50, 138, and 391 $ ha^{-1}, respectively. Given the same price for all TMPs, side dressing (the example for TMP1) has the lowest economic incentive for farmer adoption. In fact, even if it were free, the potential profit increase from using side dressing is only about 6%, which is smaller than the year-to-year variation in a farmer's profit under conventional management. The lack of a strong economic incentive discourages farmers from adopting side dressing. In contrast, improved hybrids offers the largest profit potential—as much as 50% over their profit without hybrids. Presumably, the same would be true if even better hybrids were to replace currently used hybrids. However, to achieve this higher profit, a higher N rate is required, which results in more energy consumption and likely more reactive N pollution.

Economic and Environmental Impact of Technologies and Management Practices Priced as $ kg N^{-1}

When TMPs are priced as $ kg N^{-1}, the optimized N rate for each TMP shifts toward the optimized N rate at higher fertilizer prices, considering $Pr_{fert,i} = Pr_{fert} + Pr_{TMP,i}$. Taking ESN as an example, if applying ESN increases the cost by $0.91 kg N^{-1} (equivalent to baseline fertilizer price), the optimized N application rate for ESN is 119 kg N ha^{-1} (blue circle with number 2 in Fig. 4). Even though two of the TMP cases—side dressing and improved—hybrids, are not usually priced as $ kg N^{-1}, we still examine their dynamics here because (i) their cost could be connected to N application rates by policies such as a N tax and (ii) other TMPs (e.g., controlled-released fertilizers) that are priced as $ kg N^{-1} may have a similar impact on yield response functions in some circumstances.

As the TMP price increases (e.g., the blue circle moves toward 4 and 10 in Fig. 4 and 5), the overall expenditure related to N rate ($Pr_{fert,i}$) increases. This leads to a decrease in the optimal N application rate to the point at which marginal revenue matches marginal cost and results in decreasing excess N and farmer profits. Technologies and management practices in the upper left quadrant have a positive impact on farmer profit and the environment (evaluated by N application rates in Fig. 4 or excess N in Fig. 5); TMPs in the upper right quadrant have a positive impact on farmer profit but a negative impact on the environment. By contrast, TMPs in the lower-left quadrant have the opposite impact as those in the upper right. No TMPs fall in the lower right quadrant because, by definition, TMPs cannot have negative impacts on both farmer profits and the environment. Among the three TMP cases, only improved hybrids can lead to a higher N rate when the TMP price is lower than $2.17 kg N^{-1}. Similarly, only improved hybrids can lead to higher excess N when the TMP price is lower than $0.80 kg N^{-1}. Overall, higher TMP prices lead to lower N application rates and lower N losses but reduce the economic incentive for their adoption.

Impact of Technologies and Management Practices Implementation on N Use Efficiency

The implementation of TMPs does not necessarily lead to NUE improvement. The impact of TMP implementation on NUE is different for NUE_r and NUE_p and also varies under different TMP pricing schemes.

When TMPs are priced in $ ha^{-1}, the implementation of side dressing, ESN, and improved hybrids lead to improvements in NUE_r (compare the circles labeled "1" in Fig. 6a). However, the implementation of improved hybrids leads to an insignificant change in NUE_p, whereas the other two TMP cases lead to improvements in NUE_p (compare the circles labeled with "1" in Fig. 6b).

When TMPs are priced in $ kg N^{-1}, the TMP price affects the impact of TMP implementation on NUE. As the price of a TMP increases (e.g., the blue circle moves toward 4 and 10 in Fig. 6), NUE_r and NUE_p increase, whereas the economic incentives for adopting TMPs decrease. Therefore, a maximum NUE_r and NUE_p that does not reduce farmer profits relative to the baseline exists for each TMP. For example, the maximum NUE_r levels for side dressing, ESN, and improved hybrids are 0.65, 0.51, and 0.52 kg N kg N^{-1}, respectively (the NUE_r level where the TMP line crosses the horizontal dotted line in Fig. 6a).

Technologies and Management Practices Options to Achieve Positive Environmental and Economic Impact

Overall, the implementation of a TMP can have a positive impact on farmer profits and all environmental parameters, including optimal N application rates (X^*), excess N loss (N_{exc}^*), and planting area (PA*). Figure 7 summarizes the impact of all three TMP cases on the economic and environmental parameters and highlights the TMP price ranges that create positive outcomes for all examined parameters.

Side dressing (TMP1) has a positive environmental impact on X^* and N_{exc}^* despite the TMP price variation but has a negligible impact on PA*. However, to increase farmer profits (Fig. 7a), TMP price should be lower than 50 $ ha^{-1} or 0.61 $ kg N^{-1}.

Environmentally Smart N (TMP2) increases farmer profits only when its price is lower than 138 $ ha^{-1} or 1.13 $ kg N^{-1}. At this price (or lower), implementing ESN would have a positive impact on all three environmental parameters (Fig. 7b). The price of ESN is currently 0.44 $ kg N^{-1}, which is within the range for economic and environmental benefits (Blaylock, 2013).

Improved hybrids (TMP3) lead to a negative impact on the environment by increasing X^* and N_{exc}^* if their cost is independent of N application rate. If the N-dependent price of improved hybrids is between 2.17 and 2.69 $ kg N^{-1} (Fig. 7c), a positive impact on all environmental parameters and farmer profits occurs. If the sole environmental target were lower excess N, the price of the improved hybrid should be between 0.80 and 2.69 $ kg N^{-1}. Even though the improved hybrid is not currently priced in $ kg N^{-1}, such a price adjustment for ensuring a positive environmental impact could be achieved by several policies, such as a N tax.

Applying different yield response functions in the literature to the analysis above leads to similar results, which are summaried in the supplementary materials. To ensure positive economic and environmental outcomes for all yield response functions used in the sensitivity test, the price for side dressing should be lower than 50 $ ha^{-1} or 0.61 $ kg N^{-1}, and the price for ESN should be lower than 138 $ ha^{-1} or 0.86 $ kg N^{-1} (Table 4). No pricing scheme is feasible for improved hybrids to increase farmer profits and reduce N application at the same time. If reducing excess N is the sole environmental target, then charging a N tax

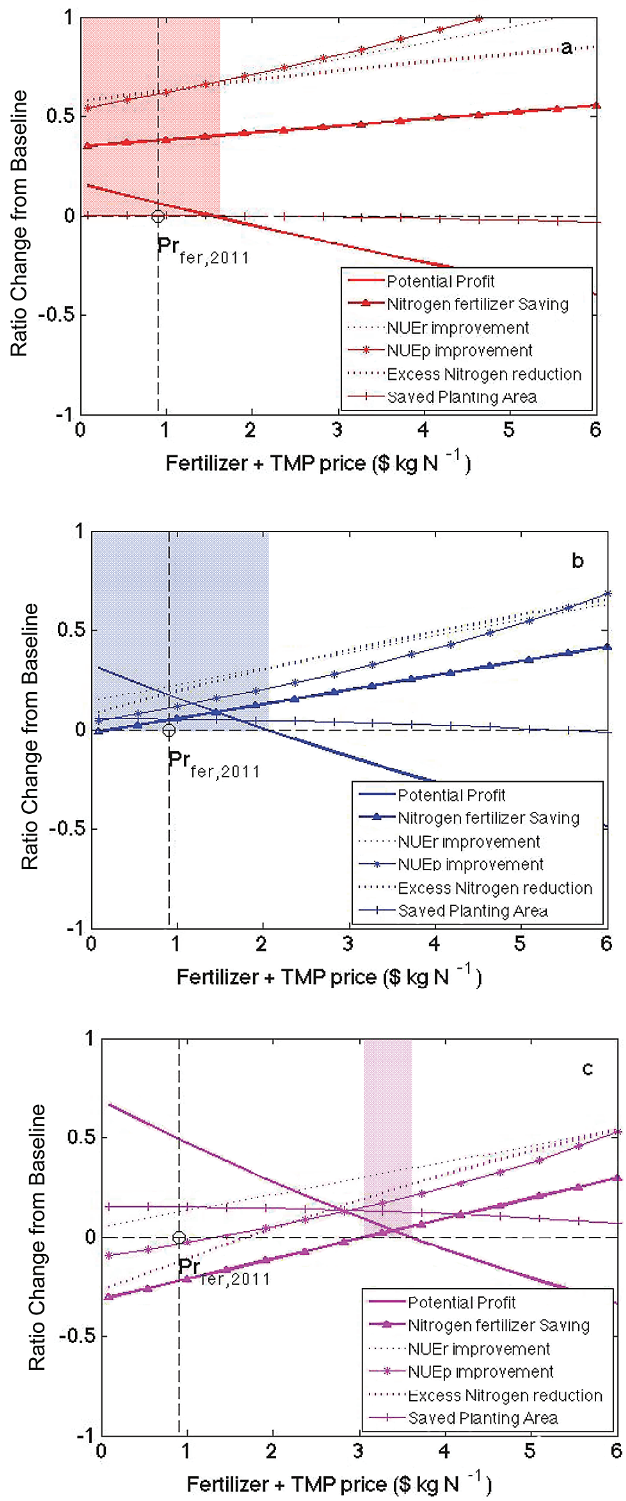

Fig. 7. The impact of the technologies and management practice (TMP) price on farmer profits, N fertilizer saving, N use efficiency (NUE), excess N, and planting area. The value on the *y* axis is the ratio of an economic or environmental parameter changed after implementing (a) TMP1 (side dressing), (b) TMP2 (Environmentally Smart Nitrogen), and (c) TMP3 (improved hybrid). For example, the "changed ratio" for potential profit is the difference between the optimal profit before and after implementing TMPs divided by the profit before implementing TMPs [$(\pi_i^* - \pi^*)/\pi^*$]. A positive value in the graphs suggests a positive impact on farmer profits or the environment. The red, blue, and magenta boxes demonstrate the price range for TMP1, TMP2, and TMP3, respectively, to ensure positive impact on farmer's profit and all environmental parameters.

Table 4. Case study: price ranges that guarantee positive economic and environmental outcomes for implementation of three technologies and management practices for corn from the midwestern United States.

TMP† case	TMPs priced as $ ha^{-1}	TMPs priced as $ kg N^{-1}
Side dressing (Gehl et al., 2005)	0–50	0–0.61
ESN‡ (Blaylock, 2013)	0–138	0–0.86
Improved cultivar (Ciampitti and Vyn, 2012)	NA	0.89–1.96§

† Technologies and management practice.

‡ Environmentally Smart Nitrogen.

§ No pricing scheme exists for improved hybrids that increase farmer profits and reduce nitrogen application rates at the same time. The price range here only achieves the environmental objective of reducing excess N.

within a range of 0.89 to 1.96 $ kg N^{-1} would help to achieve positive economic and environmental outcomes, given all of the assumptions of these calculations.

Monetized Environmental Benefits of Excess N Reduction

Using preliminary estimates of the monetized environmental costs of reactive N pollution, the cost to society of N lost from cropland is comparable to farmer profits (Fig. 5). For example, in the baseline scenario, the environmental cost of N pollution due to excess N is approximately 2756 $ ha^{-1} (674–4660 $ ha^{-1}, calculated by Eq. [6]), which is about three times farmer profits per hectare. Implementing side dressing can reduce environmental costs to 1030 $ ha^{-1} (252–1742 $ ha^{-1}), a savings of 1726 $ ha^{-1} (422–2918 $ ha^{-1}).

This suggests that policies providing additional economic incentives for farmers to adopt TMPs will lead to overall societal benefits. However, this cost-benefit analysis is not only preliminary but is also incomplete. For example, the societal costs of fossil fuel demand and greenhouse gas emissions from the Haber-Bosch process used to produce N fertilizer are not included. Conversely, the benefits to society of producing food at affordable costs to consumers are also not included.

Discussion

N Use Efficiency Dynamics in Technologies and Management Practices Implementation

For all TMPs that follow the quadratic-plateau yield response pattern, NUE (including NUE_r and NUE_p) decreases as N application rates increase due to the diminishing yield response to N application. As a result, the NU for each TMP is not a static variable. It is affected by TMP's yield response function and fertilizer-to-crop price ratios.

Our case studies suggest that implementing TMPs may have different impacts on NUE_r and NUE_p and may, counterintuitively, lead to increasing excess N and N application rates in some cases.

Improving NUR_r by implementing TMPs does not necessarily result in an increase in NUE_p. According to Eq. [3] and [4], $NUE_p = (NUE_r/NC) + (Y_0/X)$. Therefore, if the optimal N application rate increases, NUE_p may decrease while NUE_r increases from the baseline case. Although NUE_r was improved in all TMP cases, implementing TMP2 and TMP3 caused little change in NUE_p (Fig. 6b; compare the circles labeled "1" for the TMPs relative to the base case).

Similarly, implementing TMPs can have the counter-intuitive effect of increasing NUE_r and excess N when the optimized N application rate increases (Eq. [5]). However, the increasing NUE_r and N application rate also indicates an increasing yield level. As a result, implementing such TMPs may have an environmental benefit in sparing naturally vegetated land from farming.

Technologies and Management Practices Profit Potential

The weak economic incentive to use side dressing compared with ESN and improved hybrids applies to other TMPs that do not raise the baseline yield ceiling (e.g., TMP1 in Table 3 for a corn field in the midwestern United States). In Eq. [10], when

$$R < \frac{\sqrt{(Y_{max} - Y_0)Y_{max}}}{5X_{max}}$$

then

$$\frac{Pr_{fert}^{\ 2} \cdot X_{max}^{\ 2}}{4(Y_{max} - Y_0)Pr_{crop}} < Pr_{crop} \cdot Y_{max} / 100$$

Therefore, we can assume that $(Pr_{fert}^{\ 2} \cdot X_{max}^{\ 2})/[4(Y_{max} - Y_0)Pr_{crop}]$ is negligible, and the equation can be simplified to

$$\pi^* \approx A\left(-Pr_{fert} \cdot X_{max} - Cost_{other} + Pr_{crop} \cdot Y_{max}\right) \qquad [14]$$

The same assumption applies to π_i^*. As a result, the potential profit for implementing TMP_i is $Pr_{crop} \cdot (Y_{max,i} - Y_{max}) - Pr_{fert} \cdot (X_{max,i} - X_{max})$. Therefore, the potential profit for implementing a TMP is determined by how much the TMP increases the yield ceiling and/or how much the TMP reduces the N application rate at the yield ceiling. Assuming that $Y_{max,i} - Y_{max} = e \cdot Y_{max}$ and $X_{max,i} - X_{max} = -f \cdot X_{max}$ ($e > 0$ and $f > 0$), the potential profit increase due to a N application rate reduction can only be equivalent to the potential profit increase due to a yield ceiling increase, when $e/f = (X_{max}/Y_{max})R$.

Such an analysis could be applied to most corn farms in the midwestern United States because 21 of 22 rainfed farms and all irrigated farms reported in Setiyono et al. (2011) have

$$\frac{\sqrt{(Y_{max} - Y_0)Y_{max}}}{5X_{max}} > R \ \ (R = 4.14) \text{ and } (X_{max}/Y_{max}) \cdot R < 0.1.$$

As a result, TMPs that can increase yield ceilings by only 10% (e.g., improved hybrid and irrigation) would have a greater profit potential than TMPs that solely reduce N application rate at the yield ceiling (TMP1).

Technologies and Management Practices Price Range for Positive Environmental and Economic Impact

The TMP price range for positive economic and environmental impact is affected by how TMPs change the yield response function. To characterize such relations for corn farms in the midwestern United States, we simplified the equations for parameters examining TMPs' environmental and economic impact (Table 5). The simplification is based on the assumption that

$$\frac{\sqrt{(Y_{max} - Y_0)Y_{max}}}{5X_{max}} > R$$

following the analysis described above. Table 6 summarizes the conditions that the TMP must meet to ensure a positive impact on each environmental or economic parameter.

For TMPs that do not increase the yield ceiling (TMP1), the TMP price should be lower than $Pr_{fert} \cdot (X_{max} - X_{max,i})$ \$ ha^{-1} or $Pr_{fert}[(X_{max}/X_{max,i}) - 1]$ \$ kg N^{-1} to ensure profitability, whereas no condition is needed to obtain a positive or neutral impact on environmental parameters.

The TMPs that increase the yield ceilings (TMP2 and TMP3) usually provide a greater profit margin and land-sparing benefits but lead to an increase in N application rates and excess N lost. The requirement for a TMP to reduce N application rates is more strict than to reduce excess N losses because TMP2 and TMP3 always have higher yield increases due to application $\{NC[(Y_{max,i} - Y_{0i}) - (Y_{max} - Y_0)] > 0\}$.

Impact of Fertilizer and Crop Product Prices

The impact of TMPs on environmental and economic parameters will shift depending on changes in the prices of traditional N fertilizer and crop products. For most corn farms in the midwestern United States, or any farm that complies with the condition that

$$\frac{\sqrt{(Y_{max} - Y_0)Y_{max}}}{5X_{max}} > R$$

economic incentives for implementing TMP1 and TMP2 (the TMPs that do not increase N application rates at the yield ceiling or $X_{max,i} \le X_{max}$) increase as the price for traditional fertilizer increases. However, the environmental benefits of TMP implementation on N application rate and excess N decrease (Table 6). In contrast, economic incentives for implementing TMP3 ($X_{max,i} > X_{max}$) decrease as traditional fertilizer prices increase. The environmental benefits increase with the fertilizer price only if

$$\frac{X_{max,i}^{\ 2}}{Y_{max,i} - Y_{0,i}} - \frac{X_{max}^{\ 2}}{Y_{max} - Y_0} > 0$$

An increase in crop price provides more economic incentive for farmers to implement TMP2 and TMP3 (the TMPs that increase yield ceiling or $Y_{max,i} \ge Y_{max}$) but does not provide additional economic incentives for the implementation of TMP1. The impact of crop price on environmental benefits is more complex. The environmental benefits of implementing TMPs increase as the crop price increases for most TMPs, except TMPs have a bigger impact on increasing N application–related cost than NUE improvement at the yield ceiling:

$$\frac{X_{max,i}^{\ 2}}{Y_{max,i} - Y_{0,i}} - \frac{X_{max}^{\ 2}}{Y_{max} - Y_0} > 0$$

where a TMP is priced in \$ ha^{-1}, and

$$\frac{(Pr_{fert} + Pr_{TMP,i}) \cdot X_{max,i}^{\ 2}}{Y_{max,i} - Y_{0,i}} - \frac{Pr_{fert} \cdot X_{max}^{\ 2}}{Y_{max} - Y_0} > 0$$

where a TMP is priced in \$ kg N^{-1}.

Policy Implications

Our analysis suggests that the implementation of TMPs often leads to a reduction in the N application rate or an improvement in NUE, but this is not always the case. The environmental benefits associated with implementing a particular TMP are also determined by fertilizer, crop, and TMP prices. Therefore, policies that affect these prices can influence outcomes and help achieve desired environmental goals, such as reducing reactive N pollution or N fertilizer consumption. Even so, designing such policies involves considering the relevant yield response function and the available TMPs. Our NUE^3 framework was developed to investigate the environmental and economic impacts of TMPs and can be applied to provide qualitative and quantitative analysis of relevant policy options.

Policies that increase fertilizer prices, such as a levying a N tax or discontinuing fertilizer subsidies, can reduce N fertilizer consumption and reactive N pollution in two ways: (i) If TMPs are not available, farmers would need to reduce their N application rate as the fertilizer-to-crop price ratio increases, and (ii) if TMPs are available, farmers confronting fertilizer price increases would likely adopt TMPs with lower N application rates (TMP1 and TMP2; $X_{max,i} \le X_{max}$), especially because the economic incentives for adopting such TMPs would have increased.

When coupled with available TMPs, policies such as ethanol subsidies and market factors that affect crop prices have a complex impact on N fertilizer consumption and reactive N pollution. When TMPs are not available, higher crop prices could also lead to a higher N application rate, which would help maximize the farmer's profit. When TMPs are available, a higher crop price would provide additional economic incentive for farmers to adopt TMPs that have a higher yield ceiling (TMP2 and TMP3; $Y_{max,i} \ge Y_{max}$). Doing so may result in a higher N application rate, which may or may not be counteracted by improved NUE.

Subsidizing TMPs typically encourages more efficient N management in cropland. However, to achieve their intended environmental benefits, these policies would need to be targeted appropriately. For example, to ensure a positive impact on all economic and environmental parameters, the subsidy should adjust the TMP price to ranges similar to those listed in Table 6, which will change as fertilizer and crop prices vary. However, policies that solely provide economic incentives may not be enough to encourage farmers to adopt more efficient N management practices. Our analysis assumes that farmers will adopt any practice that is optimal for maximizing profit. Some TMPs, such as ESN and precision farming analyzed in our study, can improve farmer profits but have not been widely applied, mainly due to social and logistical barriers that limit behavioral change among farmers (Prokopy et al., 2008). Consequently, policies to improve NUE must be accompanied by efforts to build effective communication channels with farmers and efforts to increase their access to TMPs and related technical support.

Conclusions

The implementation of technologies and management practices (TMPs) has complex impacts on farmer profits and the environment. Applying the NUE^3 framework to a corn

Table 5. Impacts of technologies and management practices implementation on economic and environmental parameters for corn-producing farms in the midwestern United States. These conditions are also applicable to any other cases where $\frac{\sqrt{(Y_{max}-Y_0)Y_{max}}}{5X_{max}} > R$ **.**

	TMPs† priced as \$ ha^{-1}	TMPs priced as \$ kg N^{-1}
Farmer's profit (dπ*)	$Pr_{crop}\cdot(Y_{max,i}-Y_{max})-Pr_{fert}\cdot(X_{max,i}-X_{max})-Pr_{TMP,i}$	$Pr_{crop}\cdot(Y_{max,i}-Y_{max})-Pr_{fert}\cdot(X_{max,i}-X_{max})-Pr_{TMP,i}\cdot X_{max,i}$
N application rate (dX*)	$(X_{max,i}-X_{max})-\frac{R}{2}(\frac{X_{max,i}^2}{Y_{max,i}-Y_{0,i}}-\frac{X_{max}^2}{Y_{max}-Y_0})$	$(X_{max,i}-X_{max})-\frac{Pr_{fert}}{2Pr_{crop}}\cdot\left(\frac{X_{max,i}^2}{Y_{max,i}-Y_{0,i}}-\frac{X_{max}^2}{Y_{max}-Y_0}\right)-\frac{\left(\frac{Pr_{TMP,i}}{Pr_{crop}}\right)X_{max,i}^2}{2(Y_{max,i}-Y_{0,i})}$ or $(X_{max,i}-X_{max})-\frac{1}{Pr_{crop}}\cdot\left[\frac{Pr_{fert}}{2}\left(\frac{X_{max,i}^2}{Y_{max,i}-Y_{0,i}}-\frac{X_{max}^2}{Y_{max}-Y_0}\right)+\frac{Pr_{TMP,i}X_{max,i}^2}{2(Y_{max,i}-Y_{0,i})}\right]$
Excess N (dNexc*)	$(X_{max,i}-X_{max})-\frac{R}{2}\left(\frac{X_{max,i}^2}{Y_{max,i}-Y_{0,i}}-\frac{X_{max}^2}{Y_{max}-Y_0}\right)$ $-NC[(Y_{max,i}-Y_{0,i})-(Y_{max}-Y_0)]$	$(X_{max,i}-X_{max})-\frac{Pr_{fert}}{2Pr_{crop}}\cdot\left(\frac{X_{max,i}^2}{Y_{max,i}-Y_{0,i}}-\frac{X_{max}^2}{Y_{max}-Y_0}\right)-$ $\frac{\left(\frac{Pr_{TMP,i}}{Pr_{crop}}\right)X_{max,i}^2}{2(Y_{max,i}-Y_{0,i})}-NC[(Y_{max,i}-Y_{0,i})-(Y_{max}-Y_0)]$
Planting area (dPA*)	$P/Y_{max,i}-P/Y_{max}$	$P/Y_{max,i}-P/Y_{max}$

† Technologies and management practices.

Table 6. Technologies and management practice conditions that ensure a positive effect on environmental or economic parameters for corn producing farms in the midwestern United States. These conditions are applicable to any other cases where $\frac{\sqrt{(Y_{max}-Y_0)Y_{max}}}{5X_{max}} > R$.

	TMPs† priced as \$ ha⁻¹ (e.g., side dressing)	TMPs priced as \$ kg N⁻¹ (e.g., ESN‡)
Farmer's profit	$Pr_{TMP,i} \le Pr_{crop}\cdot(Y_{max,i}-Y_{max}) - Pr_{fert}\cdot(X_{max,i}-X_{max})$	$Pr_{TMP,i} \le \frac{1}{X_{max,i}}[Pr_{crop}\cdot(Y_{max,i}-Y_{max}) - Pr_{fert}\cdot(X_{max,i}-X_{max})]$
N fertilization rate	$\left(X_{max,i}-X_{max}\right) - \frac{R}{2}\left(\frac{X_{max,i}^{2}}{Y_{max,i}-Y_{0,i}} - \frac{X_{max}^{2}}{Y_{max}-Y_0}\right) \le 0$	$Pr_{TMP,i} \ge Pr_{crop}\frac{2\left(Y_{max,i}-Y_{0,i}\right)}{X_{max,i}^{2}}\left[\frac{R\cdot X_{max}^{2}}{2\left(Y_{max}-Y_0\right)} + \left(X_{max,i}-X_{max}\right)\right] - Pr_{fert}$
Excess N	$\left(X_{max,i}-X_{max}\right) - \frac{R}{2}\left(\frac{X_{max,i}^{2}}{Y_{max,i}-Y_{0,i}} - \frac{X_{max}^{2}}{Y_{max}-Y_0}\right) - NC[(Y_{max,i}-Y_{0,i})-(Y_{max}-Y_0)] \le 0$	$Pr_{TMP,i} \ge Pr_{crop}\frac{2\left(Y_{max,i}-Y_{0,i}\right)}{X_{max,i}^{2}}\left[\frac{R\cdot X_{max}^{2}}{2\left(Y_{max}-Y_0\right)} + \left(X_{max,i}-X_{max}\right) - NC[(Y_{max,i}-Y_{0,i})-(Y_{max}-Y_0)]\right] - Pr_{fert}$
Planting area	$Y_{max,i} - Y_{max} \ge 0$	$Y_{max,i} - Y_{max} \ge 0$

† Technologies and management practices.

‡ Environmentally Smart Nitrogen.

production case in the midwestern United States, we found that TMPs that do not increase yield ceilings (TMP1; e.g., side dressing) always lead to a reduction in N application rate and excess N lost. However, they do not increase environmentally desirable land-sparing practices, and the economic incentives for farmers to adopt them are small. In contrast, TMPs that increase the yield ceilings (TMP2 and TMP3; e.g., ESN, improved hybrids) have land-sparing environmental benefits and may provide greater economic incentives to farmers. However, implementing these TMPs may lead to one or more negative environmental effects, such as higher N application rates and more excess N lost to the environment.

Our study suggests that price mechanisms that affect fertilizer, crop, or TMP prices can be used to reduce N application rates and excess N losses. However, such mechanisms should be designed only after a thorough investigation of the available TMPs and their economic and environmental impacts. Our analytical framework can provide important input to such investigations and, in turn, to policy design.

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