The economic and environmental consequences of implementing nitrogen-efficient technologies and management practices in agriculture

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Key words:
nitrogen use efficiency, nitrogen fertilization rate, farmer profits, nitrogen pollution, bio-economic model

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Abstract

Technologies and management practices (TMPs) that reduce the application of nitrogen fertilizer while maintaining crop yields can improve nitrogen use efficiency (NUE), and are important tools for meeting the dual challenges of increasing food production and reducing nitrogen pollution. However, because farmers operate to maximize their profits, incentives to implement TMPs are limited, and,TMP implementation will not always reduce nitrogen 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, nitrogen fertilizer consumption, nitrogen losses, and cropland demand.

Our analytical analyses show that TMPs' impact on farmers economic decision-making and the environment is affected by how TMPs change the yield ceiling and the nitrogen fertilization rate at the ceiling, as well as how the prices of TMPs, fertilizer, and crops vary. TMPs that increase the yield ceiling appear to create a greater economic incentive for farmers than TMPs that do not, but may result in higher nitrogen application rates and excess nitrogen 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 Midwest U.S. to demonstrate how NUE^3 can be applied to farmer's economic decision-making and policy analysis.

Our NUE^3 framework provides an important tool for policy makers to understand how combinations of fertilizer, crop, and TMP prices affect the possibility of achieving win-win outcomes for both farmers and the environment.

Introduction

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 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). TMPs are different from Best Management Practices (BMPs) in that inputs are optimized in BMPs to reach production and environmental targets, while only some, but not all TMPs, could qualify as optimized BMPs.

Although more TMPs have become both available and affordable and NUE has increased in some regions, NUE has stagnated globally and 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 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, in order 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: 1) how TMPs change the yield response to N inputs; 2) 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 in order to provide pre-planting, in-season, or post-season 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 employed to determine economically optimal N fertilization rates (EONR) (Cerrato and Blackmer, 1990; Hong et al., 2007; Sawyer et al., 2006; Yadav et al., 1997). In the U.S. 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 non-linear 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 nitrogen 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 provide a better evaluation on the effect of a nitrogen 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 nitrogen's environmental impacts throughout the nitrogen 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 in order 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 Midwest U.S. , 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.

Method: description of NUE^3 framework

Our framework includes three components (Figure 1): 1) a yield response module, using a quadratic-plateau yield response function to characterize yield response to N application; 2) an optimization module, optimizing the N application rate for maximizing farmer profits based on a cost-benefit analysis; and 3) 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 nitrogen can significantly limit yield, especially when the soil nitrogen 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 application rate. The format of the function is a quadratic-plateau yield response relationship, which is commonly used to determine optimal N application rates (Cerrato and Blackmer, 1990; Sawyer et al., 2006)

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

In the equation, 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:

$$Y = \begin{cases} Y_0 + \frac{2(Y_{max} - Y_0)}{X_{max}} X - \frac{(Y_{max} - Y_0)}{{X_{max}}^2} X^2 & (X \leq X_{max}) \\ Y_{max} & (X > X_{max}) \end{cases} \quad (2)$$

In the equation, 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 $X_{max} > 0$.

NUE 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 nitrogen recovery efficiency (NUE_r, measured in kg N harvested kg^{-1} N applied – Equation 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 – Equation 4), which is the ratio of crop yield to N fertilizer applied:

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

$$NUE_p = \frac{Y}{X} \quad (4)$$

where NC is the nitrogen 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, while NUE_p is a direct measure of yield response to N input. NUE_p data is more available on both farm and global scales.

To evaluate the impact of TMPs on the environment, we use three indicators:

1) 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).

2) 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 $PA = P/Y$.

3) Excess N (N_{exc}). We define excess N as the nitrogen applied to cropland that is not taken up by crops (equation 5), and assume it is lost to the environment in a variety of forms, with negative environmental impacts occurring along the nitrogen cascade (Galloway et al., 2003).

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

Admittedly, nitrogen dynamics in soil is very complex, which involvs processes such as plant uptake, immobilizaiton, mineralization, nitrification, denitrification, and leaching. Nitrogen left in the environment may accumulate as soil nitrogen, but we assume that, over the long term, the changing rate of soil nitrogen stock is negligible compared to the nitrogen input, including fertilizer, biological fixation, manure, and deposition (Bouwmanet 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 (eg. 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 (eg. increased climate change from N_2O emissions, 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:

$$EC = \sum_j N_{exc} \cdot Frac_j \cdot DC_j \tag{6}$$

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 ($Frac_j = EF_j / \sum_j EF_j$). 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 nitrogen 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 equation 7) as the difference between revenues from crop production and the costs of N fertilizer and other operating costs ($Cost_{other}$) (USDA, 2013).

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

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 equations (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:

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

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

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

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

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

As a result, if the production function remains constant for a given farm (ie. 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 equation 8. Consequently, ${NUE_r}^*$and P/Y^* increase , while $Y^*$and ${N_{exc}}^*$ decrease (according to equation 5,9,11, and 13). The impact of an increase in R on profit is more complex. By examining equation 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: TMP 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 (Figure 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 (${X_i}^*$, ${N_{exc,i}}^*$,${PA_i}^*$, ${\pi_i}^*$) 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:

$$d\pi^* = {\pi_i}^* - \pi^*,$$

$$dX^* = {X_i}^* - X^*,$$

$$d{N_{exc}}^* = {N_{exc,i}}^* - {N_{exc}}^*, \text{ and}$$

$$dPA^* = {PA_i}^* - PA^*.$$

When $d\pi^*$>0, $dX^* < 0$, $d{N_{exc}}^* < 0$, and $dPA^* < 0$, 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 also 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 Midwestern U.S. corn, 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 (including 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 U.S. (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):

TMP 1: Achieves the standard yield ceiling ($Y_{max,1} = Y_{max}$) at a lower N application rate ($X_{max,1} < X_{max}$);

TMP 2: Reaches a higher yield ceiling ($Y_{max,2} > Y_{max}$) at the same or lower application rate ($X_{max,2} \leq X_{max}$);

TMP 3: 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, U.S. 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 nitrogen fertilizer) derived from extensive field experiments in U.S. corn belt (Blaylock et al., 2005; Blaylock, 2013; Nelson et al., 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 examine 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$_i$ ($Y_i^{\prime} = \frac{Y_i - Y_0}{Y_{max} - Y_0}$, $X_i^{\prime} = \frac{X_i}{X_{max}}$). As a result, the normalized yield response function is:

$$Y_i^{\prime} = \begin{cases} A_i + B_i X_i^{\prime} + C_i X_i^{\prime\,2} & (X_i^{\prime} \le -B_i/2C_i) \\ -B_i^2/4C_i + A_i & (X_i^{\prime} > -B_i/2C_i) \end{cases}$$

A_i, B_i, 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 Midwest U.S., although the parameters may change based on local circumstances. The resulting yield response functions are used as input in the following analysis.

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 find the economically optimal N application rate for maximizing farmer profits, according to equations 8-13, was 134 kg N ha^{-1}. The resulting NUE_r and excess N were 0.39 kg N kg^{-1} N and 82 kg N ha^{-1}, respectively.

Given the same farm and same nitrogen management practices, the economically optimal nitrogen application rate declines if the fertilizer-to-corn price ratio increases due to an increase in fertilizer price (Figure 3a). As a result, farmer profits decrease (Figure 3a), NUE_r improves (Figure 3b), excess N loss decreases (Figure 3c), and demand for planting area (PA) increases. Similarly, the same increase in the fertilizer-to-corn price ratio caused by a decreasing corn price will also lead to the same reduction in N application rate and excess N, and the same improvement in NUE, but will lead 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 will follow the same trends in farms that do and do not implement a TMP (Figure 4, 5, 6).

Economic and environmental impact of TMP 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. 1)

The TMP cost is independent of the N application rate (e.g., side dressing and improved hybrids are usually priced as \$ ha^{-1}). Therefore farmer profits in equation 7 become $\pi = A \cdot (Y \cdot Pr_{crop} - X \cdot Pr_{fert} - (Cost_{other} + Pr_{TMP,i}))$, and $Pr_{TMP,i}$ is the price of TMP_i. 2) 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.

Economic and environmental impact of TMPs 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 Figure 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 by 38% , ESN reduces the N rate by only 5%, while the use of improved hybrids increase the N rate by 22%.

Similarly, the implementation of side dressing and ESN reduces excess N by 63% and 18%, respectively, while improved hybrids increase excess N by 12% (Figure 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, while 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 ha^{-1}, \$138 ha^{-1}, 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 TMPs priced as \$ kg N^{-1}

When TMPs are priced as \$ kg N^{-1}, the optimized N rate for each TMP will shift towards 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 Figure 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 1) their cost could be connected to N application rates by policies such as a nitrogen tax; and 2) 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 towards 4 and 10 in Figure 4 and Figure 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. TMPs in the upper-left quadrant have a positive impact on both farmer profit and the environment (evaluated by N application rates in Figure 4 or excess N in Figure 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 both a negative impact on farmer profits and the environment. Among the three TMP cases, only improved hybrids can possibly lead to a higher N rate when the TMP price is lower than \$2.17 kg N^{-1}. Similarly, only improved hybrids can possibly 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 TMP implementation on Nitrogen Use Efficiency

The implementation of TMPs do 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 all lead to improvements in NUE_r (compare the circles labeled “1” in

Figure 6a). However, the implementation of improved hybrids leads to an insignificant change in NUE_p, while the other two TMP cases lead to improvements in NUE_p (compare the circles labeled with "1" in Figure 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 towards 4 and 10 in Figure 6), both NUE_r and NUE_p increase while 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 kg N kg N^{-1}, 0.51 kg N kg N^{-1}, and 0.52 kg N kg N^{-1}, respectively (the NUE_r level where the TMP line crosses the horizontal dotted line in Figure 6a).

TMP 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 (Figure 7a), TMP price should be lower than \$50 ha^{-1} or \$0.61 kg N^{-1}.

ESN (TMP2) only increases farmer profits 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 (Figure 7b). The price of ESN is currently \$0.44 kg N^{-1}, 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 its cost is independent of N application rate. If the nitrogen-dependent price of improved hybrids is between 2.17 \$ kg N^{-1} and 2.69 \$ kg N^{-1} (Figure 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 kg N^{-1} 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 nitrogen tax.

Applying different yield response functions in the literature to the analysis above lead 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 nitrogen tax within a range of \$0.89- \$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 monetized environmental costs of reactive N pollution, the cost to society of N lost from cropland is comparable to farmer profits (Figure 5). For example, in the baseline scenario, the environmental cost of N pollution due to excess N is approximately \$2756 ha^{-1} (\$674 ha^{-1} -\$4660 ha^{-1}, calculated by equation 6), about three times farmer profits per ha. Implementing side dressing can reduce environmental costs to \$1030 ha^{-1} (\$252 ha^{-1} -\$1742 ha^{-1}), a savings of \$1726 ha^{-1} (\$422 ha^{-1} -\$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 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

NUE dynamics in TMP implementation

For all TMPs that follow the quadratic-plateau yield response pattern, nitrogen use efficiency (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 nitrogen use efficiency 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 NUE_r by implementing TMPs does not necessarily result in an increase in NUE_p. According to equation 3 and 4, $NUE_p = \frac{NUE_r}{NC} + \frac{Y_0}{X}$, therefore if the optimal N application rate increases, NUE_p may decrease while NUE_r increases from the baseline case. While NUE_r was improved in all TMP cases, implementing TMP 2 and TMP3 caused little change in NUE_p (Figure 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 both NUE_r and excess N when the optimized N applicaiton rate increases (equation 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.

TMP Profit potential

The weak economic incentive to use side dressing compared to ESN and improved hybrids also applies to other TMPs that do not raise the baseline yield ceiling in the baseline (e.g. TMP1 in Table 3 for a corn field in Midwest U.S.). In equation 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 $\frac{{Pr_{fert}}^2 \cdot {X_{max}}^2}{4(Y_{max}-Y_0)Pr_{crop}}$ is negligible, and the equation can be simplified to

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

The same assumption applies to ${\pi_i}^*$. As a result, the potential profit for implementing TMP$_i$ is $Pr_{crop} \cdot \left(Y_{max,i} - Y_{max}\right) - Pr_{fert} \cdot (X_{max,i} - X_{max})$. 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 $\frac{e}{f} = \frac{X_{max}}{Y_{max}} R$.

Such an analysis could be applied to most corn farms in the Midwest U.S., because 21 in 22 rainfed farms and all irrigated farms reported in Setiyono et al. (2011) have $\frac{\sqrt{(Y_{max}-Y_0)Y_{max}}}{5X_{max}} > R$ ($R = 4.14$) and $\frac{X_{max}}{Y_{max}} R < 0.1$. 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).

TMP 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 Midwest U.S., 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 in Section 4.2. Table 6 summarizes the conditions that the TMP must meet in order 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 $Pr_{fert}(\frac{X_{max}}{X_{max,i}} - 1)$ \$ kg N^{-1} to ensure profitability, while no condition is needed to obtain a positive or neutral impact on environmental parameters.

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, since TMP2 and TMP3 always have higher yield increases due to application ($NC\left[\left(Y_{max,i} - Y_{0,i}\right) - \left(Y_{max} - Y_0\right)\right] > 0$).

Impact of fertilizer and crop product prices

TMPs' impact 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 Midwest U.S. (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 $X_{max,i} \leq X_{max}$) 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 $Y_{max,i} \geq Y_{max}$), 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 bigger impact on increasing N applicaiton 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 nitrogen use efficiency, 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 involve 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 nitrogen tax or discontinuing fertilizer subsidies, can reduce N fertilizer consumption and reactive N pollution in two ways: 1) If TMPs are not available, farmers would need to reduce their N application rate as the fertilizer-to-crop price ratio increases (Section 4.1). 2) If TMPs are available, farmers confronting fertilizer price increases would likely adopt TMPs with lower N application rates (TMP1 and TMP2; $X_{max,i} \leq X_{max}$), especially since 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 that 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; $Y_{max,i} \geq Y_{max}$). 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 nitrogen 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 nitrogen 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 both efforts to build effective communication channels with farmers and to increase their access to TMPs and related technical support.

Conclusions

The implementation of TMPs has complex impacts on farmer profits and the environment. Applying the NUE^3 framework to a corn production case in the Midwest U.S., 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.

Acknowledgements

This work resulted from a conference supported by NSF Research Coordination Network award DEB-1049744 and by the Soil Science Society of America, the American Geophysical Union, The International Plant Nutrition Institute, The Fertilizer Institute, and the International Nitrogen Initiative. We would like to thank Ray Dowbenko for providing the product information of ESN. We thank Tim Searchinger for insightful suggestions.

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Figure captions

Figure 1. Flow chart of the NUE[3] framework. Blue boxes are the three major framework modules. Red boxes indicate the major inputs.

Figure 2. Relative changes of yield response to fertilizer application after implementing 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) are used. The (0,0) and (1,1) points correspond to (X_o, Y_0) and (X_{max}, Y_{max}) in the yield response function before implementation of TMPs.

Figure 3. Response of (a) farmer's net profits to fertilizer price changes and resulting (b) recovery efficiency and (c) excess nitrogen. The circles denote optimized nitrogen 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 Midwest U.S. 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 nitrogen application rate when yields reach the yield ceiling.

Figure 4. Optimized nitrogen 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 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 (ESN), 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, number 2 means the fertilizer (or fertilizer and technology) price increases to twice the baseline fertilizer price.

Figure 5. Optimized profit and resulting excess nitrogen and environment costs for different TMPs, under various fertilizer price scenarios. The green dashed line denotes where farmer profits is same as the environmental cost (calculated according to the averaged damage cost in Table 1).

Figure 6. Optimized profit and resulting NUE for different TMPs, under various fertilizer-to-crop price ratios. The (a) NUE_r is apparent nitrogen recovery efficiency, and the (b) NUE_p is partial factor productivity of applied N.

Figure 7. The impact of the TMP price on farmer profits, nitrogen fertilizer saving, NUE, excess nitrogen, and planting area. The value on the y-axis is the ratio of an economic or environmental parameter changed after implementing (a) TMP1, (b) TMP2, and (c) TMP3. 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 ($\frac{{\pi_i}^* - \pi^*}{\pi^*}$). 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 TMP 1,2,3 respectively in order to ensure positive impact

on farmer’s profit and all environmental parameters.

Table captions

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

Table 2. Summary of the input data to the framework for the case study.

Table 3 Technologies and Management Practices (TMPs) yield response scenarios.

Table 4. The price range to ensure positive economic and environmental outcomes for implementing three TMP cases for corn producing in Midwest US. We assume that the improvement of yield response reported in those TMP cases could be applied to all yield response functions examined in sensitivity test.

Table 5. Impacts of TMP implementation on economic and environmental parameters for most corn producing farms in Midwest U.S. These conditions are also applicable to any other case where $\frac{\sqrt{(Y_{max}-Y_0)Y_{max}}}{5X_{max}} > R$.

Table 6. Summary of TMP conditions that ensure a positive impact on each environmental or economic parameter for most corn producing farms in Midwest U.S. These conditions are also applicable to any other cases where $\frac{\sqrt{(Y_{max}-Y_0)Y_{max}}}{5X_{max}} > R$.

Tables

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

Reactive Nitrogen (Nr) species	IPCC emission factor (EF_j) (De Klein et al., 2006)	Fraction of N_{exc} emitted as Nr ($Frac_j$)	Damage cost estimation (DC_j, 2005 USD 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)

† This includes both direct and indirect emissions from nitrogen application to cropland.

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

Table 2. Case study: Input data summary

Parameter	Value	Data source
$\boldsymbol{Pr_{crop}}$	\$ 0.22 kg $^{-1}$	Corn price for U.S. heartland† in 2011 (USDA ERS, 2013)
$\boldsymbol{Pr_{fert}}$	\$ 0.91 kg N $^{-1}$	Anhydrous ammonia price for U.S. in 2011 (USDA ERS, 2013)
$\boldsymbol{Cost_{other}}$	\$ 1189 ha^{-1}	Total cost minus fertilizer cost for corn farm in U.S. heartland in 2011 (USDA ERS, 2013)
$\boldsymbol{Y_0}$	6931 kg ha^{-1}	(Below et al., 2007)
$\boldsymbol{X_{max}}$	146 kg N ha^{-1}	(Below et al., 2007)
$\boldsymbol{Y_{max}}$	10707 kg ha^{-1}	(Below et al., 2007)

†Heartland is the 12 states in the U.S. 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.

Table 3 Technologies and Management Practices (TMPs) yield response scenarios.

	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);	$Y_{max,1} = Y_{max}$ $X_{max,1} < X_{max}$	$Y'_1 = \begin{cases} 0 + 3.33X' - 2.78X'^2 & (X' \leq 0.60) \\ 1 & (X' > 0.60) \end{cases}$ 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)	$Y_{max,2} > Y_{max}$ $X_{max,2} \leq X_{max}$	$Y'_2 = \begin{cases} 0 + 2.48X' - 1.32X'^2 & (X' \leq 0.93) \\ 1.15 & (X' > 0.93) \end{cases}$ Controlled release fertilizer (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)

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

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

Table 4. Case study: Price ranges that guarantee positive economic and environmental outcomes for implementation of three TMPs for Midwestern US corn.

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

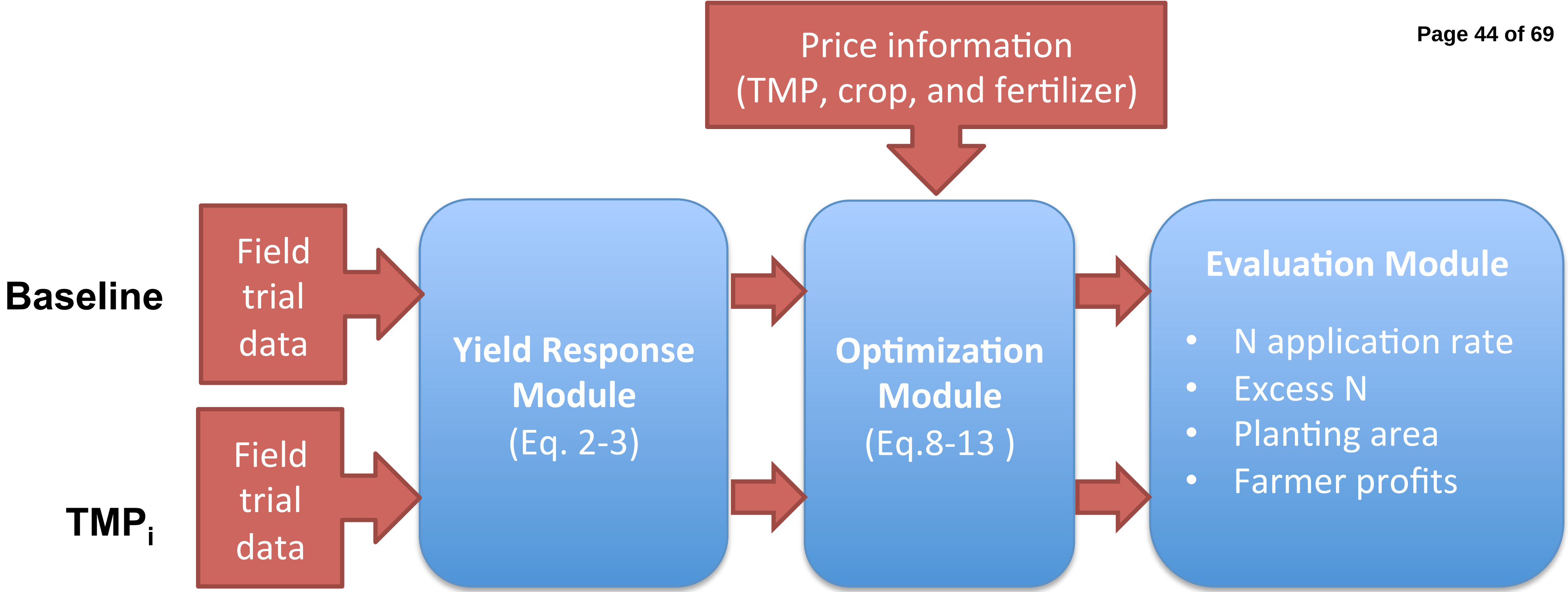
† No pricing scheme exists for improved hybrids that increase farmer profits and reduce nitrogen application rates at the same time. The price range here only achieves the environmental objective of reducing excess N.

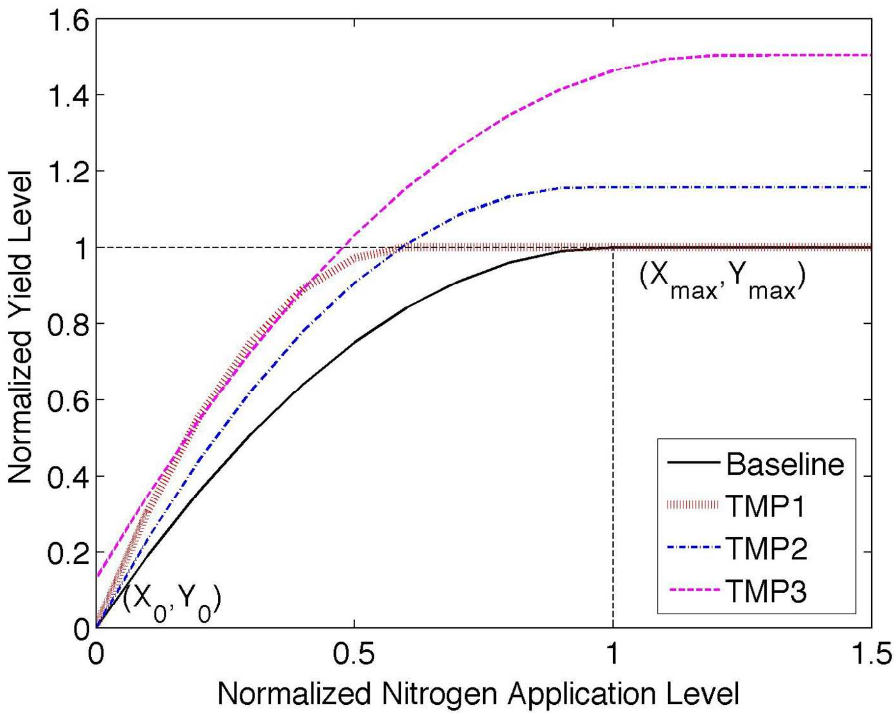
Table 5. Impacts of TMP implementation on economic and environmental parameters for Midwestern US corn producing farms. These conditions are also applicable to any other cases where $\frac{\sqrt{(Y_{max}-Y_0)Y_{max}}}{5X_{max}} > R$.

	TMPs priced as \$ ha^{-1}	TMPs priced as \$ kg N^{-1}
Farmer's Profit **($d\pi^*$)**	$Pr_{crop} \cdot (Y_{max,i} - Y_{max}) - Pr_{fert} \cdot (X_{max,i} - X_{max}) - Pr_{TMP,i}$	$Pr_{crop} \cdot (Y_{max,i} - Y_{max}) - Pr_{fert} \cdot (X_{max,i} - X_{max}) - Pr_{TMP,i} \cdot X_{max,i}$
Nitrogen 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* $(X_{max,i} - X_{max}) - \frac{1}{Pr_{crop}} \cdot [\frac{Pr_{fert}}{2}\left(\frac{X_{max,i}{}^2}{Y_{max,i}-Y_{0,i}} - \frac{X_{max}{}^2}{Y_{max}-Y_0}\right) + \frac{Pr_{TMP,i}X_{max,i}{}^2}{2(Y_{max,i}-Y_{0,i})}]$
Excess nitrogen **($dN_{exc}{}^*$)**	$(X_{max,i} - X_{max}) - \frac{R}{2}\left(\frac{X_{max,i}{}^2}{Y_{max,i}-Y_{0,i}} - \frac{X_{max}{}^2}{Y_{max}-Y_0}\right) - NC[(Y_{max,i} - Y_{0,i}) - (Y_{max} - Y_0)]$	$(X_{max,i} - X_{max}) - \frac{Pr_{fert}}{2Pr_{crop}} \cdot \left(\frac{X_{max,i}{}^2}{Y_{max,i}-Y_{0,i}} - \frac{X_{max}{}^2}{Y_{max}-Y_0}\right) - \frac{\left(\frac{Pr_{TMP,i}}{Pr_{crop}}\right)X_{max,i}{}^2}{2(Y_{max,i}-Y_{0,i})} - NC[(Y_{max,i} - Y_{0,i}) - (Y_{max} - Y_0)]$
Planting area **(dPA^*)**	$P/Y_{max,i} - P/Y_{max}$	$P/Y_{max,i} - P/Y_{max}$

Table 6. TMP conditions that ensure a positive effect on environmental or economic parameters for corn producing farms in the Midwestern U.S. 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} (e.g. side dressing)	TMPs priced as \$ kg N^{-1} (e.g. ESN)
Farmer's Profit	$Pr_{TMP,i} \leq Pr_{crop} \cdot (Y_{max,i} - Y_{max}) - Pr_{fert} \cdot (X_{max,i} - X_{max})$	$Pr_{TMP,i} \leq \frac{1}{X_{max,i}} [Pr_{crop} \cdot (Y_{max,i} - Y_{max}) - Pr_{fert} \cdot (X_{max,i} - X_{max})]$
Nitrogen fertilization rate	$\left(X_{max,i} - X_{max}\right) - \frac{R}{2} (\frac{{X_{max,i}}^2}{Y_{max,i} - Y_{0,i}} - \frac{{X_{max}}^2}{Y_{max} - Y_0}) \leq 0$	$Pr_{TMP,i} \geq Pr_{crop} \frac{2\left(Y_{max,i} - Y_{0,i}\right)}{{X_{max,i}}^2} \left[\frac{R \cdot {X_{max}}^2}{2(Y_{max} - Y_0)} + \left(X_{max,i} - X_{max}\right)\right] - Pr_{fert}$
Excess nitrogen	$\left(X_{max,i} - X_{max}\right) - \frac{R}{2}\left(\frac{{X_{max,i}}^2}{Y_{max,i} - Y_{0,i}} - \frac{{X_{max}}^2}{Y_{max} - Y_0}\right) - NC[(Y_{max,i} - Y_{0,i}) - (Y_{max} - Y_0)] \leq 0$	$Pr_{TMP,i} \geq Pr_{crop} \frac{2\left(Y_{max,i} - Y_{0,i}\right)}{{X_{max,i}}^2} \left[\frac{R \cdot {X_{max}}^2}{2(Y_{max} - Y_0)} + \left(X_{max,i} - X_{max}\right) - NC[(Y_{max,i} - Y_{0,i}) - (Y_{max} - Y_0)]\right] - Pr_{fert}$
Planting area	$Y_{max,i} - Y_{max} \geq 0$	$Y_{max,i} - Y_{max} \geq 0$


Price information
(TMP, crop, and fertilizer)
Baseline
Field trial data
TMP_i
Field trial data
Yield Response Module
(Eq. 2-3)
Optimization Module
(Eq.8-13)
Evaluation Module
• N application rate
• Excess N
• Planting area
• Farmer profits



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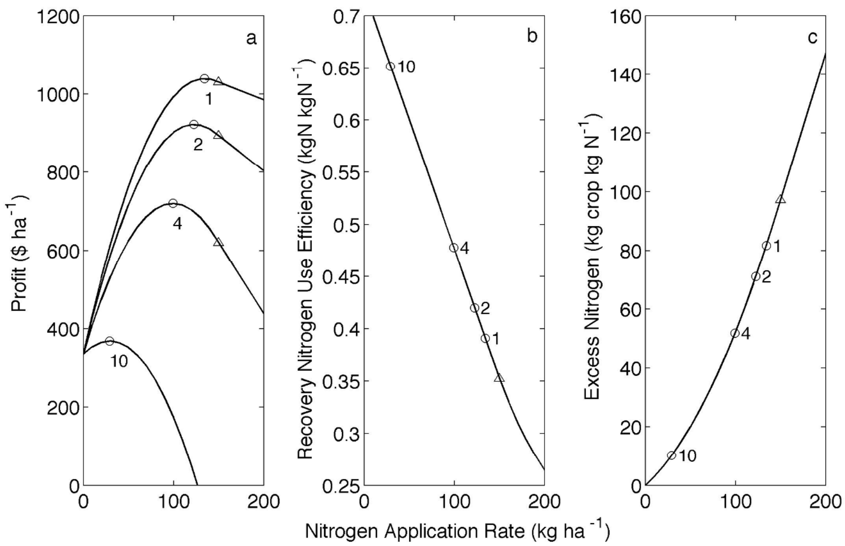

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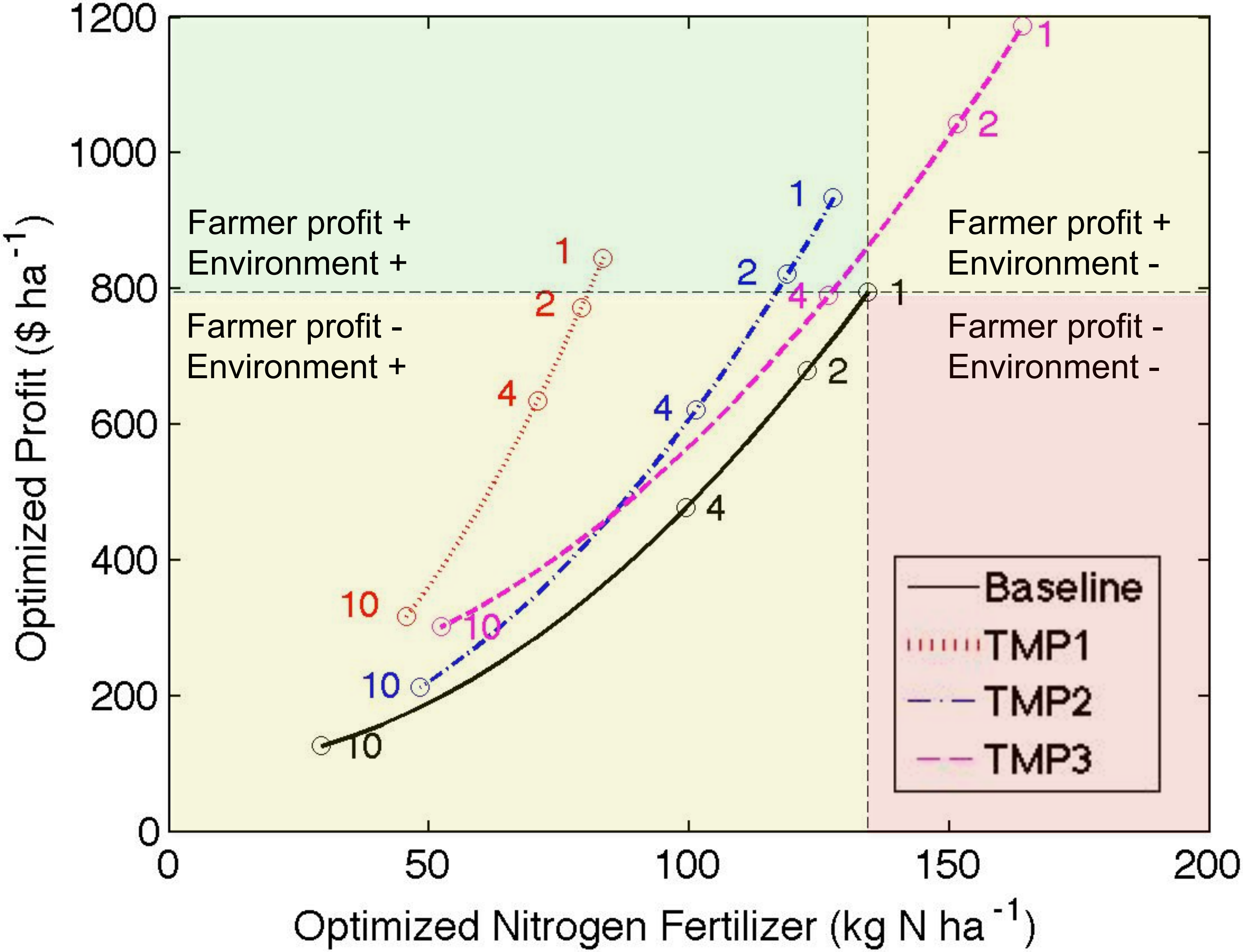
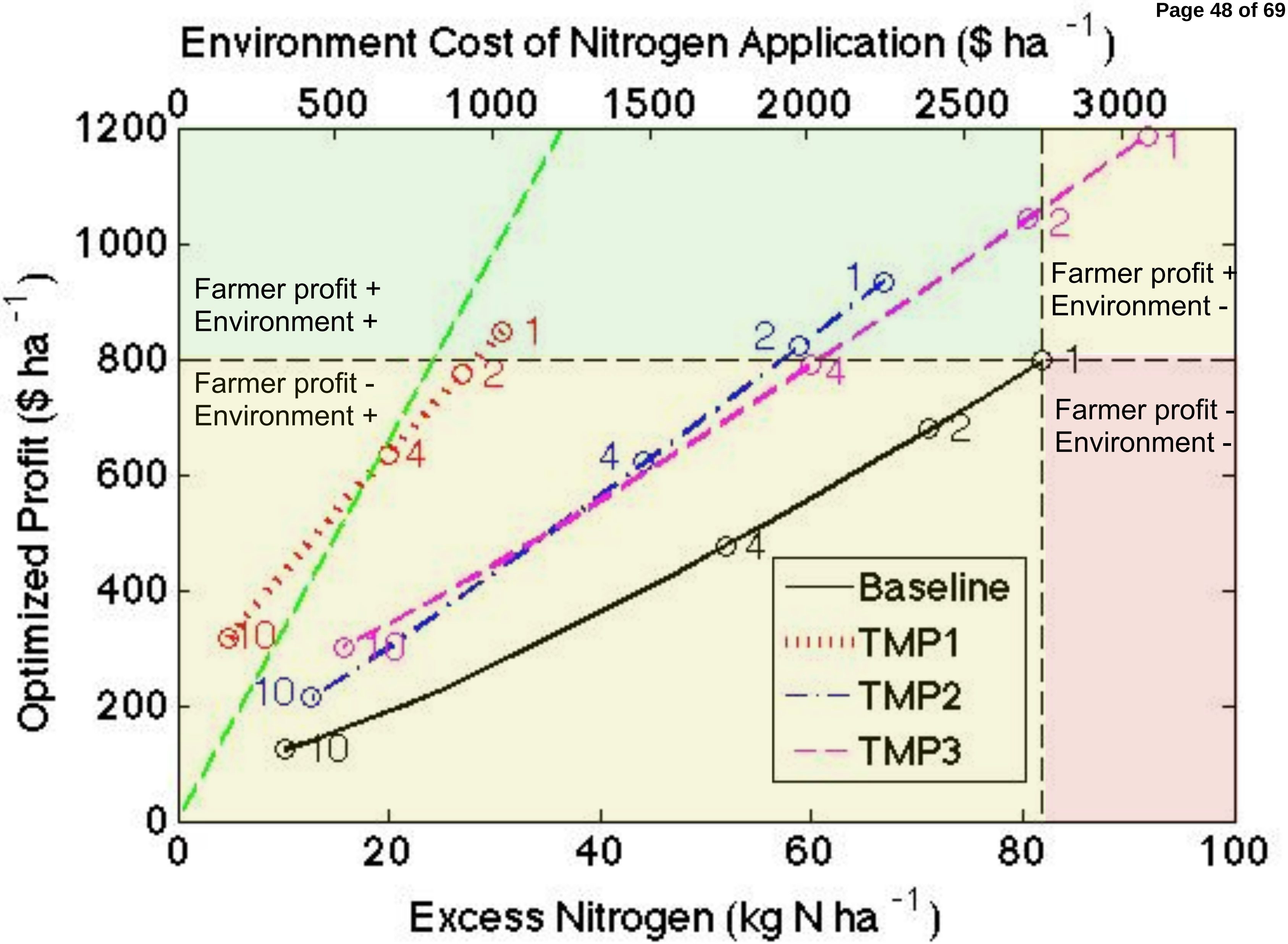
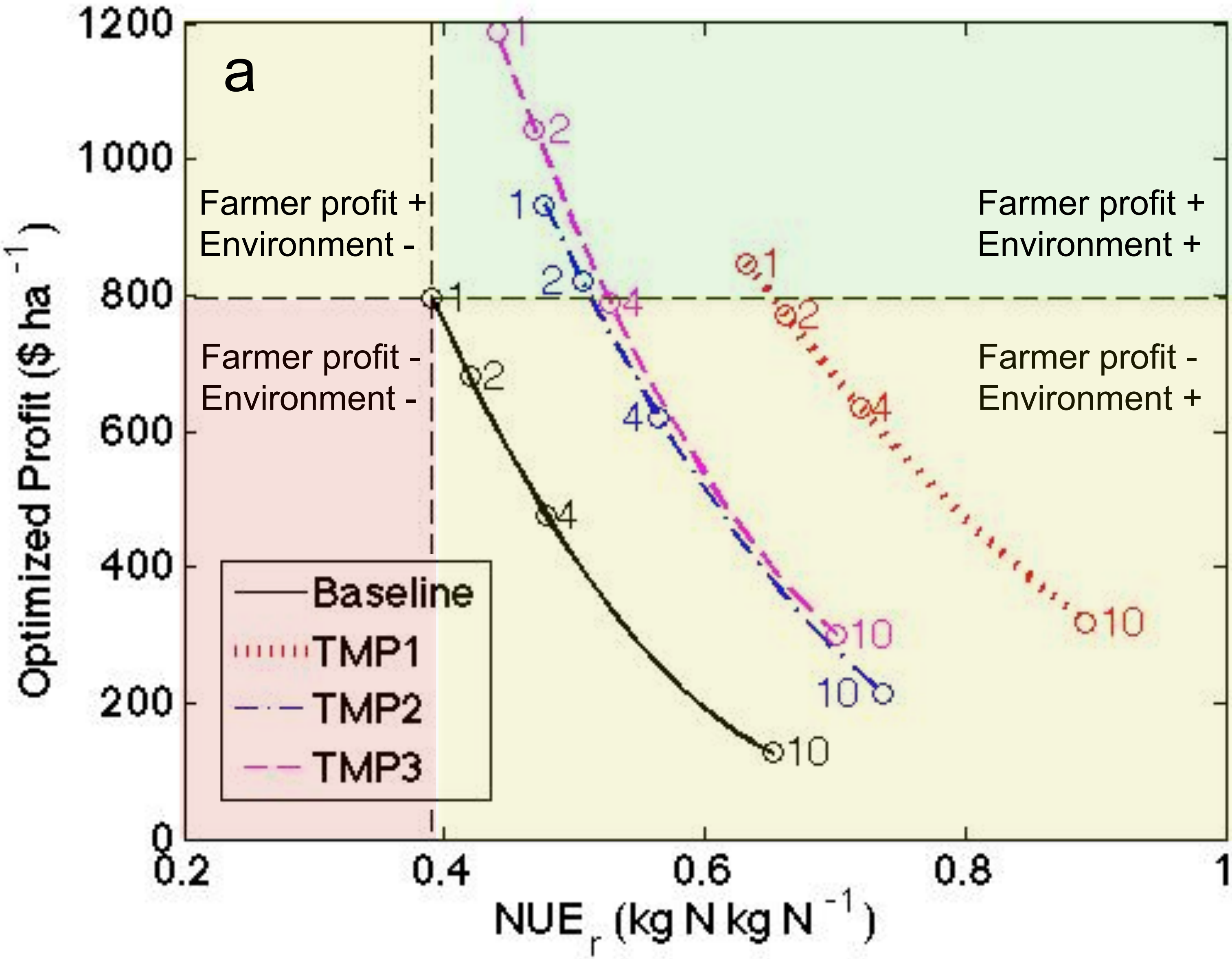
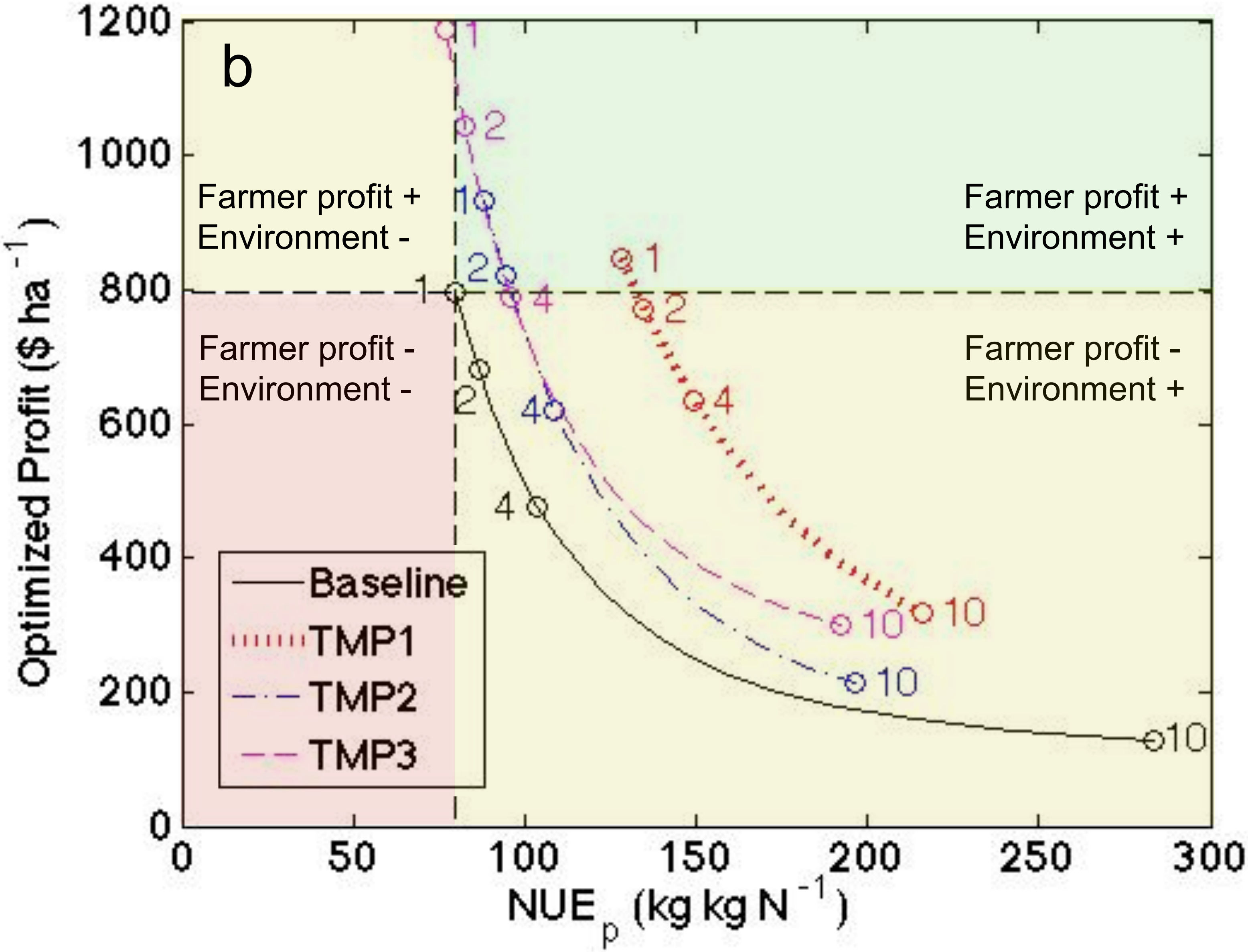

Farmer profit +
Environment +
Farmer profit +
Environment -
Farmer profit -
Environment +
Farmer profit -
Environment -
Baseline
TMP1
TMP2
TMP3
Optimized Profit ($ ha^{-1})
Optimized Nitrogen Fertilizer (kg N ha^{-1})
0
200
400
600
800
1000
1200
0
50
100
150
200
1
2
4
10

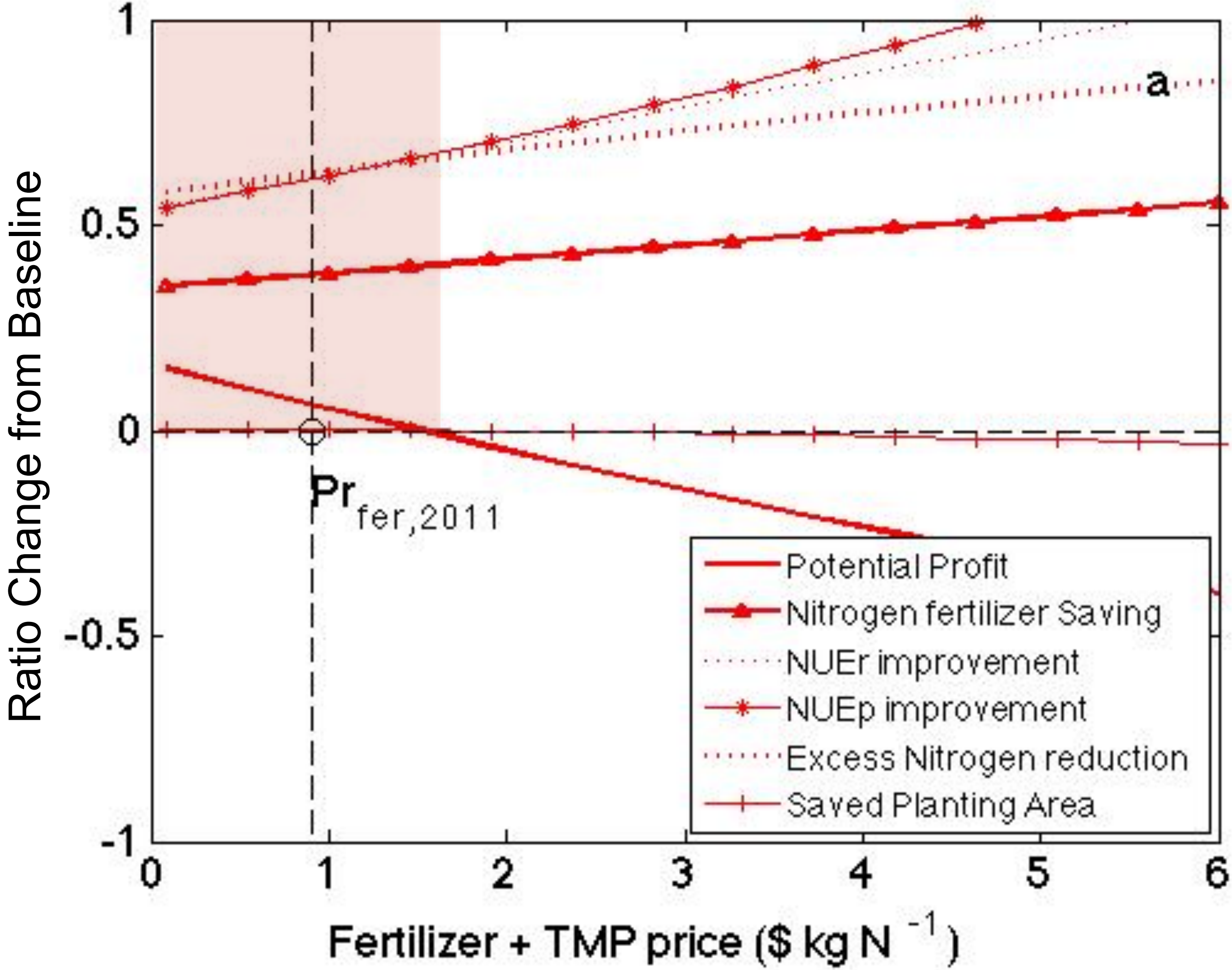


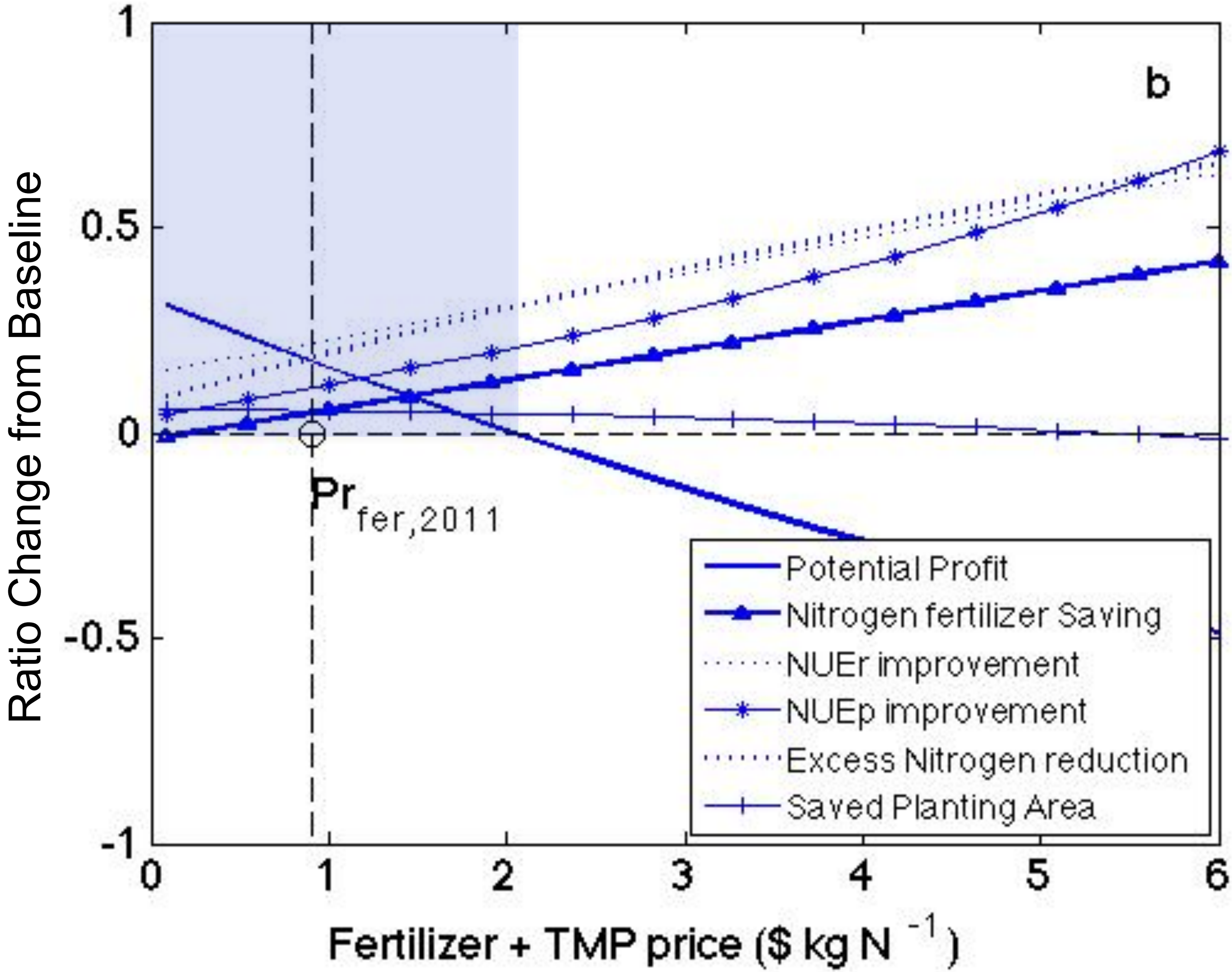
Environment Cost of Nitrogen Application ($ ha -1)
0
500
1000
1500
2000
2500
3000
1200
1000
800
600
400
200
0
Optimized Profit ($ ha -1)
Farmer profit +
Environment +
Farmer profit -
Environment +
Farmer profit +
Environment -
Farmer profit -
Environment -
Baseline
TMP1
TMP2
TMP3
0
20
40
60
80
100
Excess Nitrogen (kg N ha -1)


a
Farmer profit +
Environment -
Farmer profit +
Environment +
Farmer profit -
Environment -
Farmer profit -
Environment +
Baseline
TMP1
TMP2
TMP3
Optimized Profit ($ ha -1)
NUEr (kg N kg N -1)
0
200
400
600
800
1000
1200
0.2
0.4
0.6
0.8
1

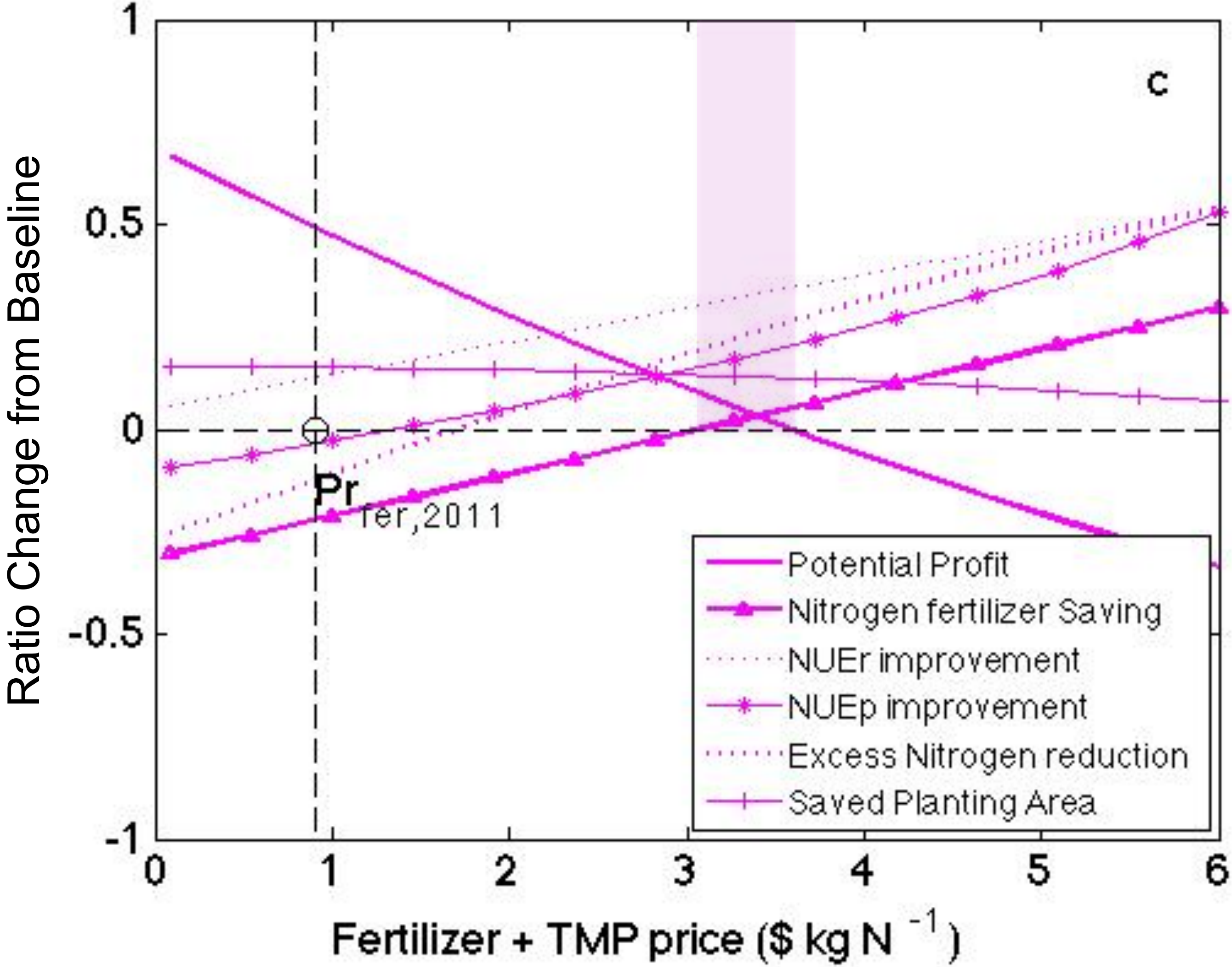


b
Farmer profit +
Environment -
Farmer profit +
Environment +
Farmer profit -
Environment -
Farmer profit -
Environment +
Baseline
TMP1
TMP2
TMP3
Optimized Profit ($ ha -1)
NUEp (kg kg N -1)
0
200
400
600
800
1000
1200
0
50
100
150
200
250
300


a
Pr fer,2011
Potential Profit
Nitrogen fertilizer Saving
NUEr improvement
NUEp improvement
Excess Nitrogen reduction
Saved Planting Area
Ratio Change from Baseline
Fertilizer + TMP price ($ kg N -1)
1
0.5
0
-0.5
-1
0
1
2
3
4
5
6



b
Ratio Change from Baseline
1
0.5
0
-0.5
-1
0
1
2
3
4
5
6
Fertilizer + TMP price ($ kg N -1)
Pr fer,2011
Potential Profit
Nitrogen fertilizer Saving
NUEr improvement
NUEp improvement
Excess Nitrogen reduction
Saved Planting Area



c
Ratio Change from Baseline
1
0.5
0
-0.5
-1
0
1
2
3
4
5
6
Fertilizer + TMP price ($ kg N -1)
Pr fer,2011
Potential Profit
Nitrogen fertilizer Saving
NUEr improvement
NUEp improvement
Excess Nitrogen reduction
Saved Planting Area

The economic and environmental consequences of implementing nitrogen-efficient technologies and management practices in agriculture

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Key words:
nitrogen use efficiency, nitrogen fertilization rate, farmer profits, nitrogen pollution, bio-economic model

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Supplementary Materials

S1. Glossary

a, b, and c: Parameters of a yield response function

A_i, B_i, and C_i: Parameters of a yield response function, normalized

e: The percentage improvement of yield plateau due to implementation of TMP$_i$ (defined in $Y_{max,i} - Y_{max} = e \cdot Y_{max}$)

f: The percentage improvement of nitrogen fertilization rate at yield plateau due to implementation of TMP$_i$ (defined in $X_{max,i} - X_{max} = -f \cdot X_{max}$)

j: Four reactive nitrogen forms, including N_2O, NO_3^-, NO_x, and NH_3

$Cost_{other}$: All the operating costs except nitrogen fertilizer (\$ ha^{-1})

DC_j: Damage cost of the reactive nitrogen j (\$ kg^{-1})

$d\pi^*$: Difference between famer profit before and after implementing a TMP (\$ ha^{-1})

dX^*: Difference between optimized fertilization rate before and after implementing a TMP (kg N ha^{-1})

$dN_{exc}{}^*$: Difference between excess N before and after implementing a TMP (kg N ha^{-1})

dPA^*Difference between cropland demand before and after implementing a TMP (ha)

EF_j: IPCC emission factors for reactive nitrogen j

$Frac_j$: Fraction of N_{exc} released to the environment in reactive nitrogen form j

N_{exc}: Excess nitrogen (kg N ha^{-1})

$N_{exc}{}^{*}$: Excess nitrogen at the optimized N fertilization rate (kg N ha^{-1})

$N_{exc,i}{}^{*}$: Excess nitrogen at the optimized N fertilization rate after implementing TMP$_i$ (kg N ha^{-1})

NC: Nitrogen content of the crop (kg N per kg crop product)

NUE_p: Partial factor productivity of applied N (kg grain yield kg^{-1} N applied)

$NUE_p{}^{*}$: Partial factor productivity of applied N when the N fertilization rate is optimized to maximize farmer profits (kg grain yield kg^{-1} N applied)

NUE_r: Apparent nitrogen recovery efficiency (kg N kg^{-1} N applied)

$NUE_r{}^{*}$: Apparent nitrogen recovery efficiency when the N fertilization rate is optimized to maximize farmer profits (kg N kg^{-1} N applied)

P: Crop production demand (kg)

PA: Planting area (ha)

PA^{*}: Planting area at the optimized N fertilization rate (kg ha^{-1})

$PA_i{}^{*}$: Planting area at the optimized N fertilization rate after implementing TMP$_i$ (kg ha^{-1})

Pr_{crop}: Crop price (\$ kg^{-1})

Pr_{fert}: Fertilizer price (\$ kg N^{-1})

R: Fertilizer to crop price ratio

X: Nitrogen application rate (kg N ha^{-1})

X_0: N fertilization rate equals 0 (kg N ha^{-1})

$X_i^{'}$: Normalized N fertilization rate of TMP_i using the yield response without TMP implementation ($X_i^{'} = \frac{X_i}{X_{max}}$)

X_{max}: N fertilization rate at the yield plateau (kg N ha^{-1})

X^*: Optimized N fertilization rate to maximize farmer profits (kg N ha^{-1})

${X_i}^*$: Optimized N fertilization rate to maximize farmer profits when implementing TMP_i (kg N ha^{-1})

Y: Yield (kg ha^{-1})

Y_0: Yield level without N fertilization (kg ha^{-1})

$Y_i^{'}$: Normalized yield level of TMP_i using the yield response without TMP implementation ($Y_i^{'} = \frac{Y_i - Y_0}{Y_{max} - Y_0}$)

Y_{max}: Yield level at the yield plateau (kg ha^{-1})

Y^*: Yield level when the N fertilization rate is optimized to maximize farmer profits (kg ha^{-1})

π: Farmer profits ($ ha^{-1})

π^*: Maximum farmer profits ($ ha^{-1})

${\pi_i}^*$: Maximum farmer profits after implementing TMP_i ($ ha^{-1})

TMP: Technologies and Management Practices

ESN: Environmentally Smart Nitrogen, a controlled-release fertilizer product.

S2. Yield response functions for corn production in the U.S.

The yield response to nitrogen application varies largely due to soil and climate conditions, management practices, and crop types. The difference in the yield response affects farmers' balance sheets and their decisions on nitrogen management practices. Therefore, we surveyed a range of yield response functions reported in the literature for corn production in the U.S. (Table S1; Figure S1).The yield level without nitrogen fertilizer application ranges from 2 to 7 ton ha^{-1}, while the yield plateau ranges from 8 to 14 ton ha^{-1}. Most, but not all, show the plateau being approached near 150 kg N ha^{-1}. It is difficult to identify any one curve as "typical" for the U.S. The curves reported by Below et al. (2007, 2009) are intermediate with respect to yield plateau, whereas the curves by Cerrati and Blackmer (1990), Haegele and Below (2013), and Sawyer et al. (2006), are intermediate with respect to yield without N addition. For the study presented in the main text, we have chosen to use the curve by Below et al. (2007), and the sensitivity of the conclusions to that choice is presented here in this supplemental analysis.

S3. Sensitivity test for using different yield response functions as baseline

We used each yield response function in Table S1 as the baseline to evaluate how sensitive economic and environmental outcomes are to the baseline yield response.

Economic and environmental impact of TMPs priced as $ ha^{-1}

When TMPs are priced as $ ha^{-1}, the optimized N application rate is not affected by TMP price. After implementing TMPs, the nitrogen fertilization rate is reduced by 38% (37%, 39%), 5% (4%, 5%) for side dressing and ESN respectively, but is increased by 22% (22%, 23%) for improved hybrid (the ratio where the dashed line crosses the vertical dotted line in Figure S2). Values reported here is the median value of all tests using yield response functions in Table S1 with the upper and lower boundaries in parentheses.

Similarly, the implementation of side dressing and ESN reduces excess N by 63% (52%, 90%) and 18% (13%, 33%), respectively, while improved hybrids increase excess N by 12% (1%, 16%) (Figure S3).

In contrast, implementing improved hybrids can increase the yield level, therefore 20% (15%, 27%) less land is required to meet to the same production demand (Figure S4). Side dressing has negligible impact on land sparing, while ESN may reduce cropland demand by 7% (5%, 11%) for the same total production.

Implementing TMPs increasing the potential profit by 10% (4%, 22%), 28% (17%, 56%), 80% (49%, 158%) respectively (the ratio where the solid line crosses the vertical dotted line in Figure S2). We consider “potential profit” as farmer’s profit before accounting for the TMP cost. Despite the large variations in the change in potential profit, side dressing provides the least increase in potential profits.

Economic and environmental impact of TMPs priced as $ kg N^{-1}$

When TMPs are priced as \$ kg N^{-1}, the optimized N application rate for each TMP decreases as TMP price increases, therefore, the economic and environmental outcomes of implementing TMP change with TMP price.

To enable a positive impact on farmer profits, TMP price for side dressing, ESN, and improved hybrid should be lower than \$0.61 kg N^{-1} (\$0.61 kg N^{-1}, \$0.61 kg N^{-1}), \$1.14 kg N^{-1} (\$0.86 kg N^{-1}, \$1.61 kg N^{-1}), and \$2.72 kg N^{-1} (\$1.96 kg N^{-1}, \$3.97 kg N^{-1}) respectively (the TMP price where the solid line crosses the horizontal dotted line in Figure S2). Despite the large variations in baseline yield response functions, TMPs would not have negative impact on planting area, as long as TMPs have positive impact on farmers profit.

At any given TMP price, implementing side dressing and ESN will reduce fertilizer application and excess nitrogen lost. However, implementing improved hybrid can only reduce nitrogen fertilizer application when TMP price is higher than \$2.20 kg N^{-1} (\$1.56 kg N^{-1}, \$3.26 kg N^{-1}), and can only reduce excess nitrogen when TMP price is higher than \$0.79 kg N^{-1} (\$0.07 kg N^{-1}, \$0.89 kg N^{-1}).

To ensure a positive impact on farmer profits and all environmental parameters (including nitrogen fertilizer application rate, excess nitrogen, and planting area) for all corn production farms summarized in Figure S1, the TMP price for side dressing and ESN should be within the range \$0-\$0.61 kg N^{-1}, \$0-\$0.86 kg N^{-1}, respectively.

However, it is difficult to find a TMP price for improved hybrid to enable such win-win outcomes for all response curves examined in this sensitivity analysis (Figure S2 c). If only considering reduced excess nitrogen as the environmental target, the TMP price for improved hybrid should be within the range of \$0.89- \$1.96 kg N^{-1} to ensure win-win outcomes for all farms (Figure S3 c).

S4. A review on related agricultural economic studies

The nitrogen use in the cropping system has been intensively studied by agricultural economists. Many studies put nitrogen use in the framework of profit maximization and investigate the impact of fertilizer price or related monetary policies on fertilizer use. For example, Huang and LeBlanc (1994) found that a nitrogen tax induces farmers to use nitrogen more efficiently; Horowitz and Lichtenberg (1993) investigated how crop insurance affects corn farmers' input use in the U.S. Midwest. Some studies suggested that uncertainties in production and output price also affect farmer’s decision on fertilizer use. Isik (2002) showed that, for a risk-averse farmer, production and output price uncertainties can change input use decisions. Isik and Khanna (2003) further developed a model of farmer decision making to determine the impacts of risk preferences and production uncertainties on adoption of site-specific technologies. Sheriff (2005) suggested production uncertainties may lead risk-averse farmers to over-apply nitrogen to the cropping systems, therefore some low-cost policies, such as nutrient management plans and variable rate technologies, may be feasible to increase profit for a farmer who over-apply nitrogen. However, quantifying the impact of production uncertainties on fertilizer use and evaluating the feasibility of policies for reducing nitrogen pollution requires a better evaluation of uncertainties in production and output price.

In addition to farm income, researchers also examined the environmental impacts of nitrogen fertilizer use in cropland, and measures to reduce such externality. While excess nitrogen use may help improve farm income when production uncertainties are large, nitrite leach to the environment is likely to incur social costs. Mapp et al. (1994) compared the economic and environmental effects of broad versus targeted nitrogen use, and found that targeted nitrogen use is more effective in reducing nitrogen losses. Similarly, Babcock and Pautsch (1998) studied how variable fertilizer application rate can help increase environmental benefits by matching fertilizer rates with a soil's productivity. Using a dynamic optimization model, Watkins, Lu, and Huang (1998) studied the effects of optimal nitrogen application rate on the long-term profitability and environment, considering the nitrogen carry-over effects. Preckel et al. (2000) investigated how contract design affects nitrogen use, and discussed the implication of contract design in reducing environmental externalities. Yadav (1997) used a dynamic optimization model to simulate the optimal level of nitrogen rate that would maintain the nitrate contamination at certain level. Berntsen et al. (2003) used a farm model to study the environmental and economic consequences of implementing difference nitrogen taxes. They found that, to achieve efficiency, different farm type should implement different taxation scheme for reduction of nitrate leaching. Although the environmental cost from nitrogen may not be considered by all the farmers, leading to a possible negative externality, other input use, such as pesticide could directly affect farmer health (Antle and Pingali, 1994).

Since nitrogen use in the cropping system has a major impact on water pollution, some researchers studied the water and nitrogen use jointly. Larson, Helfand and House (1996) found that a water surface is more efficient than a nitrogen input charge, although marginally less efficient than an emissions charge. Knapp and Schwabe (2008) demonstrated that Nitrate emission control can be "accomplished primarily through reduced applied water.

Bio-economic models, which integrate farmer's decision functions on resource management and production functions in one model, have been developed to examine the impact of policies and technologies on farmer profits and the environment (Janssen and van Ittersum, 2007; Mérel et al., 2014). Many models prescribe a fixed input intensity according to farm survey averages or a constant elasticity between input intensity and productivity (Babcock and Pautsch, 1998). Such parameterization limits the model's application in accessing policies and technologies that may affect farmer's input intensities or yield response. To address this limitation, increasing amount of studies implement non-linear production functions calibrated with field experiments or biological models (Isik and Khanna, 2003; Knapp and Schwabe, 2008; Mérel et al., 2014). For example, Mérel et al. (2014) calibrate the crop production function according to a biophysical soil process model (DAYCENT model, Del Grosso et al., 2008).

Table S1 A summary of references used in Figure S1

Reference	Reference Type	Data description
Below et al. (2007)	Conference paper	2005-2006, 37 on farm N response trials in 5 Midwestern states
Below (2009)	Conference paper	2005-2008, 78 on farm N response trials in 6 Midwestern states
Gentry et al. (2013)	Journal	2005-2010, Champaign, IL; continuous corn
Haegele and Below (2013)	Journal	2008-2009; Champaign, IL;
Setiyono et al. (2011)	Journal	The observed data are from the calibration data set from Clay Center, NE, in 2002
Cerrato and Blackmer (1990)	Journal	1985-1986, Iowa, 6 locations; 12 site-year of data, each having 10 rates of N applied
Sawyer et al. (2006)	Report	N calculator, central Illinois (estimated from website for continuous corn)
Boyer et al. (2013)	Journal	2006-2011 Tennessee; continuous corn
Yadav et al. (1997)	Journal	1987-1990, Minnesota; continuous corn

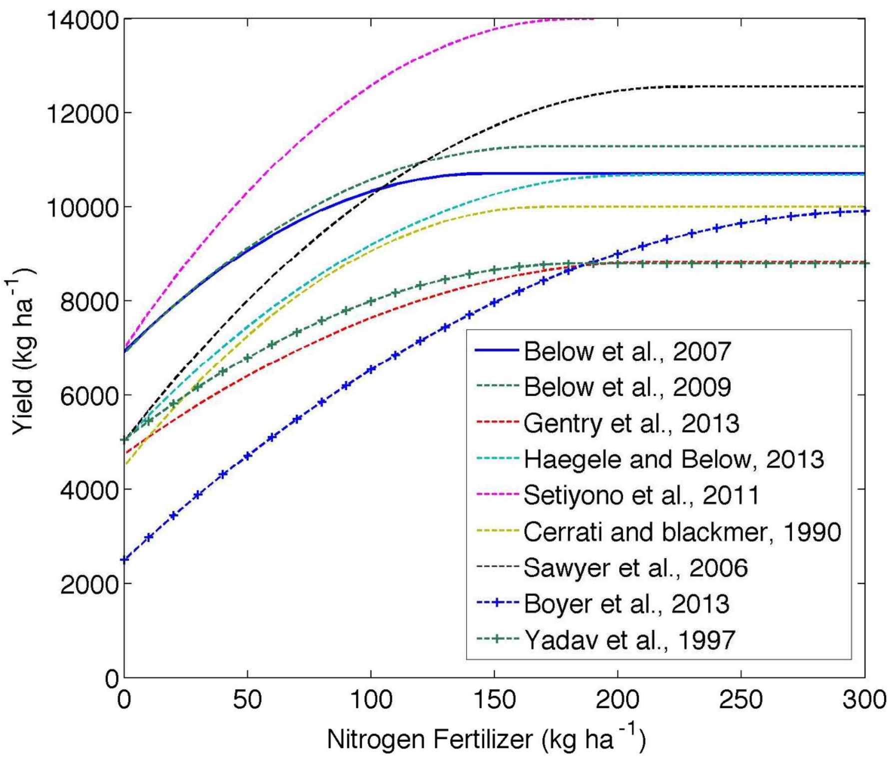

Figure S1 A summary of yield response functions reported in literatures for corn production in the US. Literatures used in Figure S1 are summarized in Table S1.

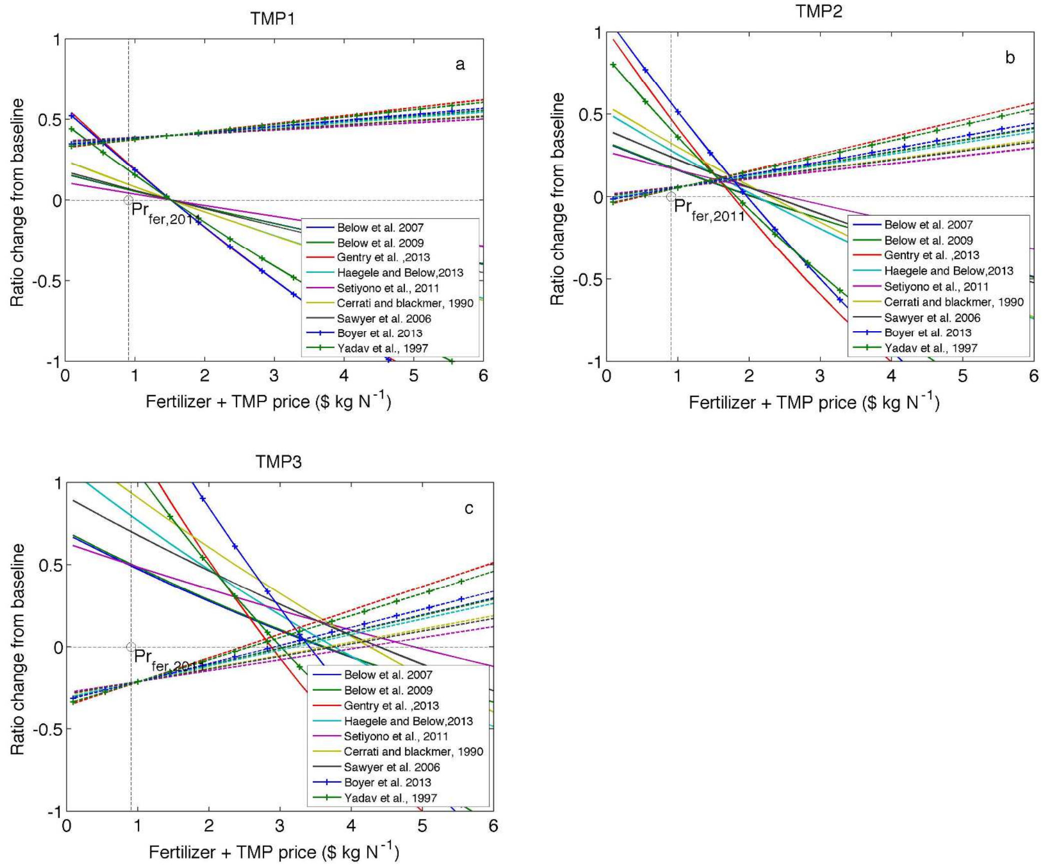

Figure S2 The impact of the TMP price on farmer profits and nitrogen fertilization rate using different baseline yield response functions reported in literatures for corn production in the US. Solid lines and dashed lines are the ratio change for farmer profits and fertilization rate respectively.

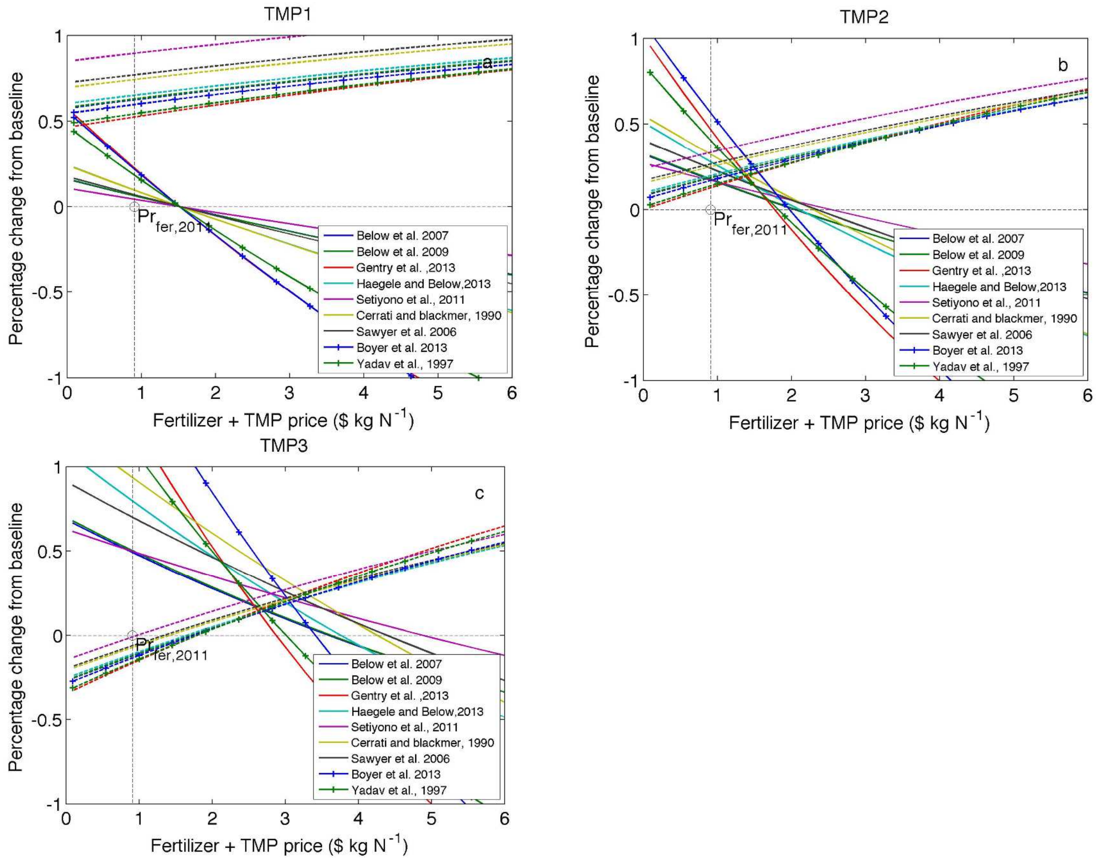

Figure S3 The impact of the TMP price on farmer profits and excess nitrogen using different baseline yield response functions reported in literatures for corn production in the US. Solid lines and dashed lines are the ratio change for farmer profits and excess nitrogen respectively.

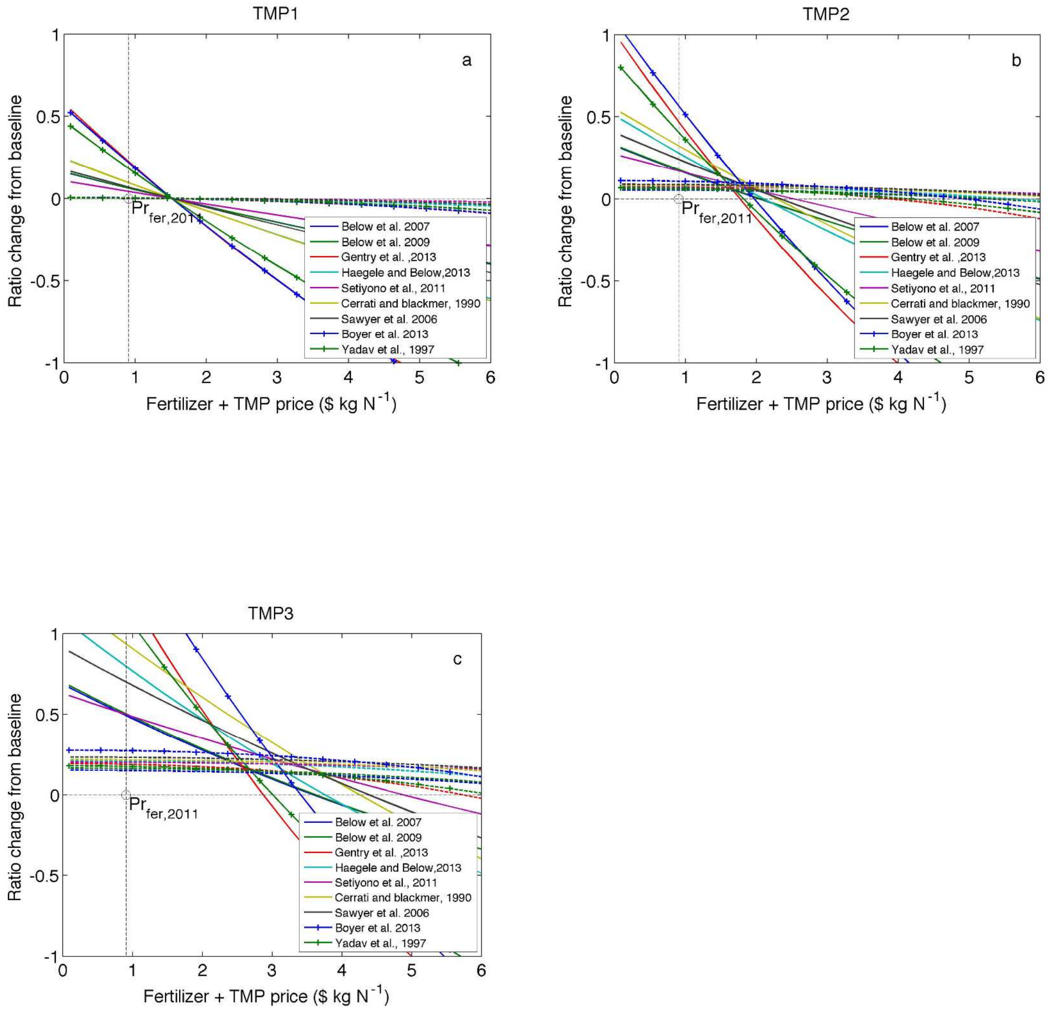

Figure S4 The impact of the TMP price on farmer profits and planting area using different baseline yield response functions reported in literatures for corn production in the US. Solid lines and dashed lines are the ratio change for farmer profits and planting area respectively.

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