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

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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 ($\$ \text{ ha}^{-1}$)
- $DC_j$: Damage cost of the reactive nitrogen $j$ ($\$ \text{ kg}^{-1}$)
- $d\pi^*$: Difference between farmer profit before and after implementing a TMP ($\$ \text{ ha}^{-1}$)
- $dX^*$: Difference between optimized fertilization rate before and after implementing a TMP (kg N $\text{ ha}^{-1}$)
- $dN_{exc}^*$: Difference between excess N before and after implementing a TMP (kg N $\text{ ha}^{-1}$)
- $dPA^*$: Difference between cropland demand before and after implementing a TMP (ha)
- $EF_j$: IPCC emission factors for reactive nitrogen $j$
\textit{Frac}_j: \text{Fraction of } N_{exc} \text{ released to the environment in reactive nitrogen form } j

\begin{itemize}
  \item \(N_{exc}\): \text{Excess nitrogen (kg N ha}^{-1}\)
  \item \(N_{exc}^*\): \text{Excess nitrogen at the optimized N fertilization rate (kg N ha}^{-1}\)
  \item \(N_{exc,i}^*\): \text{Excess nitrogen at the optimized N fertilization rate after implementing TMP}_i \text{ (kg N ha}^{-1}\)
\end{itemize}

\begin{itemize}
  \item \(NC\): \text{Nitrogen content of the crop (kg N per kg crop product)}
  \item \(NUE_p\): \text{Partial factor productivity of applied N (kg grain yield kg}^{-1} \text{ N applied)}
  \item \(NUE_p^*\): \text{Partial factor productivity of applied N when the N fertilization rate is optimized to maximize farmer profits (kg grain yield kg}^{-1} \text{ N applied)}
  \item \(NUE_r\): \text{Apparent nitrogen recovery efficiency (kg N kg}^{-1} \text{ N applied)}
  \item \(NUE_r^*\): \text{Apparent nitrogen recovery efficiency when the N fertilization rate is optimized to maximize farmer profits (kg N kg}^{-1} \text{ N applied)}
\end{itemize}

\begin{itemize}
  \item \(P\): \text{Crop production demand (kg)}
  \item \(PA\): \text{Planting area (ha)}
  \item \(PA^*\): \text{Planting area at the optimized N fertilization rate (kg ha}^{-1}\)
  \item \(PA_{i}^*\): \text{Planting area at the optimized N fertilization rate after implementing TMP}_i \text{ (kg ha}^{-1}\)
\end{itemize}

\begin{itemize}
  \item \(Pr_{crop}\): \text{Crop price (}$ \text{kg}^{-1}$\)
  \item \(Pr_{fert}\): \text{Fertilizer price (}$ \text{kg N}^{-1}$\)
  \item \(R\): \text{Fertilizer to crop price ratio}
  \item \(X\): \text{Nitrogen application rate (kg N ha}^{-1}\)
  \item \(X_0\): \text{N fertilization rate equals 0 (kg N ha}^{-1}\)
\end{itemize}
$X'_i$: 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$^{-1}$)

$\pi$: Farmer profits ($ha^{-1}$)

$\pi^*$: 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\textsuperscript{-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

<table>
<thead>
<tr>
<th>Reference</th>
<th>Reference Type</th>
<th>Data description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gentry et al. (2013)</td>
<td>Journal</td>
<td>2005-2010, Champaign, IL; continuous corn</td>
</tr>
<tr>
<td>Haegel and Below (2013)</td>
<td>Journal</td>
<td>2008-2009; Champaign, IL;</td>
</tr>
<tr>
<td>Setiyono et al. (2011)</td>
<td>Journal</td>
<td>The observed data are from the calibration data set from Clay Center, NE, in 2002</td>
</tr>
<tr>
<td>Cerrato and Blackmer (1990)</td>
<td>Journal</td>
<td>1985-1986, Iowa, 6 locations; 12 site-year of data, each having 10 rates of N applied</td>
</tr>
<tr>
<td>Sawyer et al. (2006)</td>
<td>Report</td>
<td>N calculator, central Illinois (estimated from website for continuous corn)</td>
</tr>
<tr>
<td>Boyer et al. (2013)</td>
<td>Journal</td>
<td>2006-2011 Tennessee; continuous corn</td>
</tr>
</tbody>
</table>

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.
Reference:


