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IMPROVING NITROGEN USE EFFICIENCY IN CROP AND LIVESTOCK PRODUCTION SYSTEMS

Reducing Nitrogen Pollution while Decreasing Farmers' Costs and Increasing Fertilizer Industry Profits

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Abstract

Nitrogen (N) pollution is emerging as one of the most important environmental issues of the 21st Century, contributing to air and water pollution, climate change, and stratospheric ozone depletion. With agriculture being the dominant source, we tested whether it is possible to reduce agricultural N pollution in a way that benefits the environment, reduces farmers' costs, and increases fertilizer industry profitability, thereby creating a "sweet spot" for decision-makers that could significantly increase the viability of improved N management initiatives. Although studies of the economic impacts of improved N management have begun to take into account farmers and the environment, this is the first study to consider the fertilizer industry. Our "sweet spot" hypothesis is evaluated via a cost-benefit analysis of moderate and ambitious N use efficiency targets in U.S. and China corn sectors over the period 2015–2035. We use a blend of publicly available crop and energy price projections, original time-series modeling, and expert elicitation. The results present a mixed picture: although the potential for a "sweet spot" exists in both countries, it is more likely that one occurs in China due to the currently extensive overapplication of fertilizer, which creates a greater potential for farmers and the fertilizer industry to gain economically from improved N management. Nevertheless, the environmental benefits of improving N management consistently dwarf the economic impacts on farmers and the fertilizer industry in both countries, suggesting that viable policy options could include incentives to farmers and the fertilizer industry to increase their support for N management policies.

Global reactive nitrogen (Nr; all nitrogen [N] compounds except N_2) pollution is one of the most critical environmental issues of our time, with an array of interconnected consequences ranging from air and water pollution to climate change and stratospheric ozone depletion (Gruber and Galloway, 2008). Consequently, a growing body of scientists and policy experts are calling for action to address its causes (e.g., Rockström et al., 2009; Kanter et al., 2013; Sutton et al., 2013; UNEP, 2013). Agricultural activities are the dominant source, with fertilizer manufacture (120 Tg N yr^{-1}) and biological N fixation by leguminous crops (50–70 Tg N yr^{-1}) being responsible for approximately 80% of global anthropogenic Nr creation (Gruber and Galloway, 2008; Sutton et al., 2013).

Efforts to improve agricultural N management focus on better synchronizing crop N supply and demand and thus affect the major users and suppliers of agricultural N: farmers and the fertilizer industry. For example, if farmers reduce their fertilizer application rates in response to a N management policy but do not simultaneously increase their N use efficiency (NUE), then their yields, and subsequently their incomes, will likely decrease. Likewise, if farmers apply (and thus purchase) less fertilizer, then fertilizer industry revenue will likely decrease unless they can offset such a reduction in sales volume with increased market penetration of new services and/or more profitable, patent-protected, high-efficiency fertilizer products. (The fertilizer industry is defined in this study as all economic actors along the N fertilizer supply chain before it reaches the farmer, from natural gas suppliers, to ammonia producers, to fertilizer manufacturers, to retailers). Thus, these stakeholders could experience negative economic impacts from policies that aim to reduce agricultural Nr pollution. To increase the likelihood of obtaining their support and hence successfully implementing N management policies, this study investigates whether an economic case for action to reduce agricultural Nr pollution exists in addition to the environmental benefits that may be achieved. In other words,

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Abbreviations: BAU, business-as-usual; EEF, enhanced efficiency fertilizer; FAO, United Nations Food and Agriculture Organization; FBMP, fertilizer best management practice; GNI, gross national income; Nr, reactive nitrogen; NUE, nitrogen use efficiency; OECD, Organization for Economic Cooperation and Development; RE, recovery efficiency.

is it possible to improve N management while reducing farmers' costs and increasing the profitability of the fertilizer industry? If such a multi-stakeholder optimum, or "sweet spot," exists, then it could potentially induce support from these stakeholders that would increase the economic and political viability of policies to improve N management at local to global scales.

The potential economic benefits to farmers of using N more efficiently are well established, underpinned by the concept that the operating costs of implementing fertilizer best management practices (FBMPs) or purchasing enhanced efficiency fertilizers (EEFs), which we define here to include slow/controlled release fertilizers and nitrification and urease inhibitors, can be offset by reduced farmer costs due to reduced fertilizer purchases (Zhu and Chen, 2002; USDA NRCS, 2003; Koch et al., 2004; Liu et al., 2006; Ortiz-Monasterio and Raun, 2007; Bates et al., 2009; Ahrens et al., 2010; Archer and Halvorson, 2010; Chen et al., 2010; Venterea et al., 2012; Blaylock, 2013).

Likewise, a number of studies have begun to quantify the economic damages of Nr pollution, including the healthcare costs of air pollution caused by NH_3 volatilization and NO_x emissions, the damage to fisheries caused by NO_3^-–induced eutrophication, and reductions in agricultural yields due to increased surface ozone (O_3) concentrations (Gu et al., 2012; Birch et al., 2011; Brink and van Grinsven, 2011; Compton et al., 2011; Avnery et al., 2011a,b; van Grinsven et al., 2013).

However, there has been little focus on the economic impacts of N management policies on the fertilizer industry. Research suggests that industry plays a key role in environmental policy, with their support often a prerequisite for success (e.g., Falkner, 2008; Fuchs, 2007; Levy and Newell, 2005). Industry will likely oppose a policy that threatens their profits, as was the case during negotiations to regulate genetically modified organisms (Clapp, 2003). Conversely, if industry sees an opportunity to increase their profits as a result of a policy, it can become a convincing proponent for action (e.g., the production phase-out of pesticides and O_3–depleting substances) (Clapp, 2003; Parson, 2003). Consequently, serious consideration of the economic impacts of improved N management policies on the fertilizer industry is an important step forward in the evaluation of different policy options for addressing agricultural Nr pollution. Indeed, an opportunity may exist for fertilizer industry actors to profit from improved N management that also benefits the environment and reduces farmer costs: N management policies could increase demand for more efficient fertilizer technologies and services that are patent protected and can be sold at a premium to customers. These new sources of revenue could potentially offset the reduction in volume of projected fertilizer sales that might be precipitated by the increase in on-farm NUE stimulated by a N management policy. The world's leading N fertilizer companies are in the process of developing and marketing EEFs (Rai, 2010), and several major companies are beginning to provide the information and technical infrastructure needed for farmers to implement FBMPs (a fertilizer "service" rather than a set of products; see, for example, Yara, 2013). In this way, the fertilizer industry's situation could be analogous to the one faced by the major manufacturers of O_3–depleting substances and pesticides: they could be both the producer of the product targeted by policy and the provider of a more sustainable, profitable alternative; this presents a valuable market opportunity. With this in mind, this paper explores the following question: Can agricultural Nr pollution be managed in such a way that the environment benefits, farmers save money, and the fertilizer industry profits?

To answer this question we focus on the corn sectors in the United States and China. Corn is the single largest consumer of agricultural N in the United States and will be in China by 2020 (FAPRI, 2011). Moreover, the U.S. and Chinese corn sectors are on divergent tracks in terms of NUE, with the amount of N needed to produce 1 Mg of corn decreasing in the United States and increasing in China over the past several decades and with considerable differences in the balance between government and market forces in each country (see Section 1 in the supplemental materials on past NUE trends, Section 4 on the factors contributing to the differences in NUE between the United States and China, and Section 10 on the history of U.S. and Chinese agricultural policy vis-à-vis farmers and the fertilizer industry). Consequently, these two countries provide considerably different contexts for testing the "sweet spot" hypothesis. In both cases we evaluate the economic impacts of two N management scenarios (one moderate, one ambitious) implemented over the period 2015–2035 on farmers, the fertilizer industry, and the environment.

In this paper, the Materials and Methods section describes the data sources and techniques used to estimate future fertilizer prices and production costs (and thus fertilizer industry profits and farmer fertilizer costs) for the period 2015–2035. We then introduce the moderate and ambitious N management scenarios used to evaluate the "sweet spot" hypothesis for corn production in the United States and China, the different strategies for implementing these scenarios, and the methods for calculating their environmental impacts. The results are followed by an analysis of whether it is possible to create a "sweet spot" in the U.S. and China scenarios where one is currently absent before concluding and providing suggestions for future research.

Materials and Methods

To test the "sweet spot" hypothesis, we developed a simple economic framework to estimate the economic impacts of the various NUE scenarios on farmer fertilizer costs and fertilizer industry profits (both in $ ha^{-1}) and the environment (in $ kg^{-1} N) using publicly available crop and energy price projections, original time-series modeling, and expert elicitation. All monetary values are in 2005 USD and future values are estimated using a 5% discount rate (Nordhaus, 2007). Figure 1 is a diagram of the model, and the following sections outline the analytical framework underpinning our calculations.

Although the data used below are taken from publications released by major international research organizations and governmental bodies and the methods are well established approaches used in statistics, agronomy, and energy economics, there are significant uncertainties inherent in any projections of future prices, yields, and other values. Consequently, the values and results described below should be viewed as our best estimates using publicly available data and published methods, which we believe reasonable for the purposes of illustrating the "sweet spot" concept. Realistically, however, prices, yields, etc. will differ from the estimates presented here.

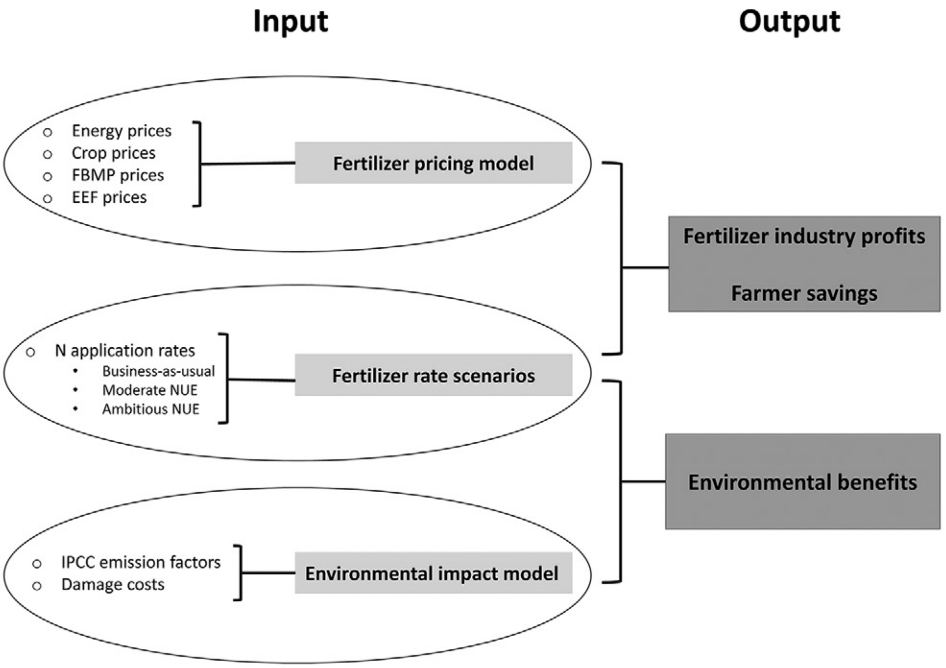

Fig. 1. Diagram of the model used to simulate industry profits, farmer savings, and environmental benefits. The "fertilizer pricing model" uses energy and crop prices to simulate traditional fertilizer prices and production costs. Costs related to fertilizer best management practices (FBMP) and enhanced efficiency fertilizers (EEF) are included when evaluating the nitrogen use efficiency (NUE) scenarios. Fertilizer application rates, both business-as-usual trends and rates under NUE scenarios, affect the economic welfare of all stakeholders, and the IPCC emission factors and damage costs that comprise the environmental impact model are central to the estimation of environmental benefits.

Projected Prices of Fertilizer in the United States and China

To project fertilizer prices in the United States and China for the period 2015–2035 (a weighted aggregation of anhydrous ammonia, urea, and urea ammonium nitrate prices for the United States and urea prices for China), forecasts were developed with autoregressive integrated moving average models using the principal determinants of historical prices (Johnston and DiNardo, 1997). These determinants are prices for natural gas, corn, and wheat in the United States and Japanese liquefied natural gas, coal, corn, rice, and wheat prices for China. Future projections of these prices are taken from recent reports by the Organization for Economic Cooperation and Development (OECD), the United Nations Food and Agricultural Organization (FAO), and the International Energy Agency (Alexandratos and Bruinsma, 2012; IEA, 2012; OECD–FAO, 2013) (see Section 2 in the supplemental materials for more detail on each approach, including projected price estimates, model equations, and evaluation).

Projected Costs of Fertilizer Production in the United States and China

Natural gas and coal are the major hydrocarbon sources used in ammonia production. The cost of fertilizer production using natural gas in the United States and China is calculated under the assumption that natural gas accounts for 75 to 90% of the cost of ammonia production (US GAO, 2003; Huang, 2007; IBISWorld, 2012) and that it takes, on average, 38 GJ to make 1 Mg of ammonia (Yara, 2012). Although natural gas is the sole hydrocarbon source for ammonia production in the United States, 71% of China's ammonia production uses coal as a hydrocarbon source (Zhou, 2010)—the remainder being 21% natural gas, and 8% oil—which is estimated to be 50 to 70% of the cost of production (Kjellberg et al., 2012; PotashCorp, 2013). The energy required to produce 1 ton of ammonia using coal is 59.4 GJ Mg^{-1} NH_3, with anthracite (comprising ~80% of the coal used in ammonia production) providing 27.2 GJ Mg^{-1} (Kahrl et al., 2010). Specific production cost equations and estimates for the United States and China can be found in the Section 2 in the supplemental materials.

Fertilizer Industry Profit Margins in the United States and China

Using the price and production cost methods outlined above, we estimated future profit margins for the U.S. and Chinese fertilizer industry out to 2035 (Fig. 2). These estimates have been adapted to include the price and cost of providing new technologies and services to measure the economic impact of the improved N management scenarios described below. The uncertainty bands in Fig. 2 are a result of the range of major published energy and crop price projections (Nelson et al., 2010; IEA, 2012; US EIA, 2013; OECD–FAO, 2013; World Bank 2013a).

We estimate industry profit per hectare and farmer fertilizer cost per hectare using Eq. [1] and [2]:

$$\text{Fertilizer industry profit per hectare} = (P_N - C_N) \times R_N \quad [1]$$

$$\text{Farmer fertilizer expenditure per hectare} = P_N \times R_N \quad [2]$$

where P_N is the N price (\$ kg^{-1} N), C_N is the N cost of production (\$ kg^{-1} N), and R_N is the N application rate (kg N ha^{-1}).

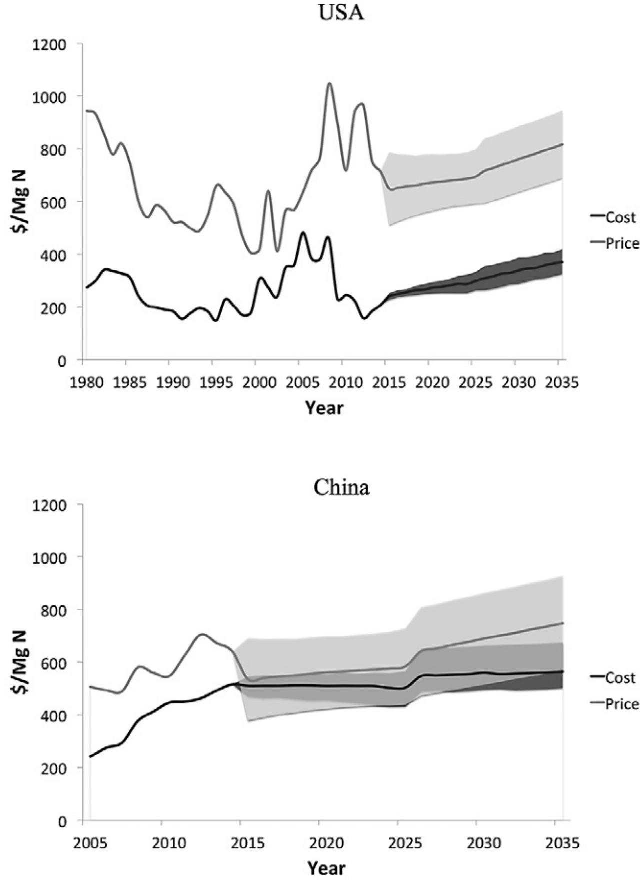

Fig. 2. Historical and projected fertilizer industry profit margins for the United States and China. The U.S. profit margin is based on an aggregated N fertilizer price and production cost (combining anhydrous ammonia, urea, and urea ammonium nitrate), whereas China's fertilizer industry profit margin is for urea. Projected margins (2013–2035) are based on OECD–FAO (2013) crop price projections and on IEA (2012) energy price projections. The uncertainty bands are a result of the range of major published energy and food price projections.

N Use Efficiency: Assumptions, Metrics, and Policy Scenarios

Based on the economic concept of input substitutability, this study assumes that the projected rate of yield increase remains constant across the different improved N management scenarios. To maintain yield while reducing N use intensity, the use of FBMPs and/or EEFs must increase. This is a conservative assumption because farmers may be able to increase, not just sustain, their yields with less N by using EEFs and/or FBMPs and/or FBMPs (e.g., Koch et al., 2004; Chen et al., 2010; Blaylock, 2013).

Fertilizer recovery efficiency (RE) (i.e., the proportion of applied N fertilizer taken up by aboveground plant biomass) is used to measure NUE:

$$\mathrm{RE} = \frac{U - U_{\mathrm{o}}}{F} \times 100 \qquad [3]$$

where U is the total N uptake by aboveground plant biomass in a plot that receives fertilizer (kg N ha^{-1}), U_{o} is the total N uptake by aboveground plant biomass in a plot that receives no fertilizer (kg N ha^{-1}), and F is fertilizer applied (kg N ha^{-1}).

Baseline N Use Efficiency and Business-as-Usual Scenarios

United States

Using USDA and agronomic literature data on corn yields, N application rates, and corn N uptake from unfertilized fields, we estimate a mean 2010–2012 RE baseline for U.S. corn of 40%. Under the business-as-usual (BAU) scenario using the OECD–FAO projections of corn yield and N application rates, RE increases to 45% in 2035 because a moderate increase in NUE is assumed to occur over time based on growing environmental concerns (Alexandratos and Bruinsma, 2012).

China

Using FAOSTAT and agronomic literature data on corn yields, N application rates, and corn N uptake from unfertilized fields in China, we estimate a mean 2010–2012 RE baseline for corn of 11%. Although this value is consistent with several field studies (e.g., Cui et al., 2008), higher RE values for maize in China have been recorded (e.g., Ju et al., 2009; Chen et al., 2010), which appear to be driven by higher yields than those reported by FAOSTAT. Under the BAU scenario, RE increases to approximately 15% in 2035 because a slight increase in NUE is assumed to occur over time (Alexandratos and Bruinsma, 2012).

See Sections 3 and 4 in the supplemental materials for more detail on the assumptions underlying these estimates and for an explanation of the significant differences in NUE between the United States and China.

Improved N Management Scenarios and Implementation Strategies

For the United States and China, we analyzed two improved N management scenarios (one moderate, one ambitious) that set RE targets above projected BAU levels (summarized in Supplemental Table S1). Our results are presented as the economic impacts of these scenarios relative to BAU. We assume here that the NUE scenarios are implemented as a condition for receiving existing agricultural subsidies. In this way, we side step a discussion of the merits and impacts of various policy mechanisms, such as a tax on traditional forms of N fertilizer or subsidies for newer products. Instead, we focus solely on how the change in fertilizer consumption and sales affects the fertilizer costs and profits of farmers and the fertilizer industry, respectively (see Section 10 in the supplemental materials for a review of U.S. and China agricultural policy vis-à-vis Nr pollution, including a discussion of several possible policy approaches to facilitate realization of the RE targets).

United States

The first, moderate U.S. scenario sets a 50% RE target (i.e., on average, 50% of applied N is recovered by U.S. corn in 2035). This is the mid-value of the reported fertilizer recoverability of U.S. corn (40–60%) (Smil, 1999; Kitchen and Goulding, 2001) and a 25% increase in RE relative to the 2010–2012 average. The 50% RE target implies a 10% reduction in the N application rate in 2035 compared with the BAU scenario.

The second, more ambitious U.S. scenario is based on the upper boundary of fertilizer recoverability in Smil (1999): a 60% RE target, corresponding to a 50% increase in RE compared with the 2010–2012 average. This would necessitate a 25% reduction in N application rates compared with the BAU scenario.

China

The moderate China scenario sets a 20% RE target. This would require a relative improvement in RE of 82% by 2035 compared with 2010–2012 levels but would still be below the RE achieved in Chinese field experiments where the synchronization of soil N supply and crop N demand was significantly improved (achieving RE levels of ~30% according to Cui et al. [2008]). The RE 20% target marks the point approximately halfway between China's current RE levels (11%) and the 31% recorded in Cui et al. (2008). The RE 20% target implies a 25% reduction in the N application rate in 2035 compared with the BAU scenario.

The ambitious China scenario sets a 30% RE target based on RE results from Cui et al. (2008). This would necessitate a 50% reduction in N application rates compared with the BAU scenario by 2035.

Implementation Strategies

We consider four implementation strategies for achieving the RE targets.

1. "No adoption": Neither farmers nor the fertilizer industry adopt or develop new practices or products in response to the RE targets. This strategy assumes that farmers reduce their N application in compliance with the RE targets but without learning new practices or purchasing new technologies to maintain their yield levels. As a result, the fertilizer industry's revenue would decrease, with little demand for new products or services given lack of farmer interest. Although farmers may be able to meet the RE target via a significant reduction in N application rate (see Eq. [3]), they could potentially suffer considerable yield decreases if nothing is done to use the remaining applied N more efficiently (Zhang et al., 2014). A limitation of the model used in this study is that it is not dynamic, meaning that reduced corn yields do not affect corn prices, when in reality yield reductions on a large-scale could result in price increases.
2. "100% FBMP": Farmers reach the target purely by using FBMPs by focusing on applying existing fertilizer types more efficiently through, for example, splitting fertilizer application into smaller applications throughout the growing season that coincide with the times that the crops most need fertilizer or using GPS technology to identify more precisely where the N requirements are in a particular field (Robertson and Vitousek, 2009).
3. "100% EEF": Farmers reach the target purely by using EEFs. In this strategy, the farmers' only action to comply with the target is the purchase and application of these new fertilizer technologies—the so-called "best management practice" is already embedded in the product.
4. "50/50": An equal mix of EEFs and FBMPs are used to achieve the RE target.

Costs of Fertilizer Best Management Practices and Enhanced Efficiency Fertilizers

To estimate the costs and benefits of following these strategies, data are required on the cost of implementing and providing FBMPs and on the price and production cost of EEFs.

Fertilizer Best Management Practices

Price estimates of FBMPs in the United States and China are taken from the International Institute for Applied Systems Analysis Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model and optimized to achieve the N rate reductions prescribed by each RE target (Winiwarter, 2005) (Supplemental Table S2). The units are in \$ kg^{-1} N reduced (i.e., the cost of reducing 1 kg of N use via a FBMP). For the United States, FBMP prices range from \$0.33 to \$0.99 kg^{-1} N reduced, depending on the RE target; for China, FBMP prices range from \$0.68 to \$0.82 kg^{-1} N reduced (Supplemental Table S2).

The cost of providing a FBMP is derived from McCann and Easter (2000), which they estimate to be approximately 60% of the cost of abatement. Although this estimate is based on U.S. agricultural conditions, it is also applied to China given the lack of a country-specific estimate. These additional costs are integrated into the farmer and fertilizer industry cost structures in Eq. [4] and [5] for both the United States and China (see also Section 5 in the supplemental materials). For the purposes of this study, we assume that the bulk of FBMPs implemented over the period 2015–2035 will be provided by industry, given the steps that major fertilizer companies are taking to develop such services (e.g., Yara, 2013) and the history of inadequate government funding (Cox, 2007; Li et al., 2013).

$$\text{Farmer's fertilizer cost}_i = (P_{\mathrm{N},i} \times \mathrm{RE}_{\mathrm{N},i}) + [P_{\mathrm{FBMP},i} \times (\mathrm{BAU}_{\mathrm{N},i} - \mathrm{RE}_{\mathrm{N},i})] \quad [4]$$

where $\mathrm{RE}_{\mathrm{N},i}$ is the N application rate under a RE scenario in year i (kg N ha^{-1}), $P_{\mathrm{FBMP},i}$ is the price to implement a fertilizer best management practice in year i (\$ kg^{-1} N reduced), and $\mathrm{BAU}_{\mathrm{N},i}$ is the N application rate under the BAU scenario in year i (kg N ha^{-1}).

$$\text{Industry profit}_i = (P_{\mathrm{N},i} - C_{\mathrm{N},i}) \times \mathrm{RE}_{\mathrm{N},i} + (P_{\mathrm{FBMP},i} - C_{\mathrm{FBMP},i}) \times (\mathrm{BAU}_{\mathrm{N},i} - \mathrm{RE}_{\mathrm{N},i}) \quad [5]$$

where $C_{\mathrm{FBMP},i}$ is the cost to provide a fertilizer best management practice in year i (\$ kg^{-1} N reduced).

Enhanced Efficiency Fertilizers

It is very challenging to find consistent price estimates for EEFs in either the academic or industry literature. Price estimates for slow/controlled release fertilizers range from a 50% to a 1200% premium over the price of a traditional N fertilizer (Lammel, 2005; Trenkel, 2010; Blaylock, 2013). Estimates for nitrification and urease inhibitors are more constrained but are still uncertain, with a range of an 8 to 100% premium above the price of traditional N fertilizer (Lammel, 2005; Laboski, 2006; Trenkel, 2010; Brink and van Grinsven, 2011). Enhanced efficiency fertilizer production cost estimates are not publicly available given their sensitive, proprietary nature.

To address this data gap, we conducted an expert elicitation of U.S. and Chinese fertilizer industry experts to better constrain these parameters. Expert elicitations are often used to characterize uncertainty on issues where information is not easily available (USEPA, 2009). Nine fertilizer industry experts from the United States and China were selected to participate in the elicitation based on their reputation as leaders in the EEF sector, the variety of disciplines they represent from agronomics to market analysis, and their willingness to participate. We solicited their expert judgment on the current price and cost of production of slow/controlled release fertilizers and nitrification and urease inhibitors, their future price and cost of production under the different RE targets, and the proportions in which they are used. Experts were asked to provide median estimates as well as 5 and 95% uncertainty bounds. We then weighted experts' responses based on their score from five seed questions about their experience and general knowledge of the EEF market. These weighted responses were pooled to provide an expert consensus (Aspinall, 2010). The seed questions, weighting, and elicitation questions are provided in the Sections 6, 7, and 8 in the supplemental material. The responses are aggregated and summarized in Supplemental Table S3. Given the comparatively wide uncertainty bounds that accompanied expert responses, estimates for the United States and China were statistically indistinguishable and are consequently aggregated in a single price and production cost estimate applicable to both the United States and China. The overall EEF premium is a weighted average of the slow/controlled release fertilizer and nitrification and urease inhibitor premiums based on their relative consumption.

Current premiums of 17% for price and 7.9% for cost are projected to be 17 and 9.3%, respectively, in 2035 under the moderate RE targets and 15 and 10%, respectively, under the ambitious targets (Supplemental Table S3). The aggregated price premiums are significantly lower than the range of price estimates cited above; this may be due to the fact that the elicitation specifically asked for information on EEFs used in broad acre crops (i.e., cereals), whereas several of the estimates cited above are for specialty crops (e.g., fruit and vegetables) where EEFs often have a higher premium (Trenkel, 2010). As with the FBMP cost estimates above, we integrate the EEF price and cost estimates into the traditional farmer and fertilizer cost structures in Eq. [6] and [7] (see also Section 5 in the supplemental materials).

$$\text{Farmer's fertilizer cost}_i = [(P_{\text{EEF},i} \times \alpha_{\text{EEF},i}) + P_{\text{N},i} \times (1 - \alpha_{\text{EEF},i})] \times \text{RE}_{\text{N},I} \quad [6]$$

where $P_{\text{EEF},i}$ is the price of enhanced efficiency fertilizer in year i (\$ kg^{-1} N), and $\alpha_{\text{EEF},i}$ is the portion of N applied as EEF, based on the assumption that a farmer applying 100% of their N as EEF reduces their N requirements by approximately 40% (Blaylock, 2013).

$$\text{Industry profit} = [(P_{\text{EEF},i} - C_{\text{EEF},i}) \times \alpha_{\text{EEF},i} + (P_{\text{N},i} - C_{\text{N},i}) \times (1 - \alpha_{\text{EEF},i})] \times \text{RE}_{\text{N},I} \quad [7]$$

where $C_{\text{EEF},i}$ is the production cost of EEF in year i (\$ kg^{-1} N).

Environmental Costs

Improving agricultural N management reduces Nr losses to the environment, which, as a result of one N atom's ability to easily interconvert among different forms, can lead to a variety of environmental and health benefits (Galloway et al., 2003). This study estimates these benefits by applying IPCC emission factors (IPCC, 2006) and peer-reviewed damage cost estimates (in \$ kg^{-1} Nr) to the difference in N application rates between the BAU and RE scenarios (Eq. [8] and Supplemental Table S5).

$$\text{Environmental benefits} = (\text{BAU}_{\text{N},i} - \text{RE}_{\text{N},i}) \times \text{EF}_j \times \text{D}_{j,i} \quad [8]$$

where EF_j is the IPCC emission factor for Nr compound j (unitless), and $\text{D}_{j,i}$ is the damage cost for Nr compound j in year i (\$ kg^{-1} N).

The IPCC emission factors quantify the direct and indirect N losses of N_2O, NO_x, NH_3, and NO_3^- from agriculture per kg N applied. Each Nr compound has a specific impact on the environment: N_2O contributes to climate change and stratospheric ozone depletion, NO_3^- to water pollution, and NO_x and NH_3 to air pollution. Although the IPCC emission factors often do not accurately replicate N loss estimates at local sites, there is evidence that these small-scale errors can cancel when aggregated to larger scales, such as countries (Del Grosso et al., 2008).

The damage cost estimates used in this study are based on attempts to monetize the economic impacts caused by the release of 1 kg of a particular Nr compound to the environment (Compton et al., 2011) or on the amount of money society is willing to pay to avoid these impacts (Brink and van Grinsven, 2011; Gu et al., 2012). The societal damages range from direct human health impacts to broader environmental consequences. For example, emerging evidence suggests that chronic exposure to NO_3^- concentrations exceeding 25 mg L^{-1} in drinking water increases the incidence of colon cancer (DeRoos et al., 2003; Grizzetti et al., 2011; van Grinsven et al., 2010), and eutrophication caused by NO_3^- leaching has been shown to reduce biodiversity.

The estimates are averaged to have one damage cost per Nr species. The considerable range between estimates stems from a variety of factors. For example, Gu et al. (2012) argue that their damage cost estimates for China are significantly lower than those for the United States and the European Union largely because they use a relatively low value of statistical life. Meanwhile, the markedly higher damage cost for NO_3^- pollution in the United States compared with the European Union is due to the economic impact of the fisheries decline in the Gulf of Mexico sparked by NO_3^-–induced eutrophication, whereas the EU estimate is based on a Scandinavian citizen's willingness to pay for a "healthy Baltic." These disparities are apparent for all the major Nr species (Supplemental Table S5), indicating significant differences in what Nr pollution effects are included and excluded in these estimates. This makes the calculation of environmental damages from Nr pollution a particularly uncertain exercise. Consequently, the values used in this study should be viewed as illustrative, with this field a crucial area of future research.

The damage cost estimates used in this study are adjusted to U.S. and China gross national income (GNI) per capita to better reflect their respective national economic conditions (an approach adopted from van Grinsven et al. [2013]). For example, Brink and van Grinsven (2011) estimate a total damage cost for N_2O of \$13 kg^{-1} N_2O–N based on the average EU citizen's willingness to pay. However, because GNI per capita is higher in the United States than in the EU (\$50,120, compared with \$33,609 in 2012) (World Bank, 2013b), U.S. society has a higher willingness to pay to avoid the damages from 1 kg of N_2O–N (\$19 kg^{-1} N_2O–N). Similarly, China's GNI per capita is much lower than the EU (\$5,740 compared with \$33,609) (World Bank, 2013b), resulting in a significantly lower willingness to pay to avoid 1 kg of N_2O–N (\$2.2 kg^{-1} N_2O–N). This approach is applied to all damage cost estimates (Supplemental Table S5).

Results and Discussion

United States

Farmers and the Fertilizer Industry

In both RE scenarios, the average 20-yr fertilizer cost per hectare for farmers is reduced relative to BAU regardless of the implementation strategy. The opposite is true for the fertilizer industry, with profits consistently lower than BAU, implying that the "sweet spot" cannot be achieved in the United States using current price/cost estimates of EEFs and FBMPs (Fig. 3). Nevertheless, the economic consequences of the "no adoption" response to the RE targets is more severe for both stakeholders: farmers are projected to lose a significant portion of their projected corn revenue due to reduced yields (10–20%), and reduced sales negatively affect projected fertilizer industry profits (4–11%) relative to BAU.

Environment

Reductions in N pollution over 20 yr range from 2.5 Tg N in the RE 50% scenario to 6.4 Tg N in the RE 60% scenario (Table 1). In both RE scenarios, the environmental benefits (\$46–115 billion) dwarf the fertilizer industry losses (\$0.7–2.2 billion) and farmer savings, ranging from a loss of \$0.6 billion to savings of \$3 billion (Fig. 4; Supplemental Table S6). This is because the cost to society of N losses (ranging from \$8.2 to \$39.4 kg^{-1} N, depending on the Nr species) vastly outweighs the cost of N fertilizer based on the monetization assumptions adopted here (\$0.75 kg^{-1} N in 2010 and projected to increase to \$0.96 kg^{-1} N in 2035) (Fig. 2). The savings from reduced NO_3^- losses eclipse the other environmental benefits for two reasons: (i) it has the highest IPCC emission factor (30% compared with 1.3% for N_2O and 5% for NO_x and NH_3), and (ii) it has the highest average damage costs (\$39.4 kg NO_3–N^{-1} compared with \$24.6 kg^{-1} NO_x–N, \$13.7 kg^{-1} NH_3–N, and \$8.2 kg^{-1} N_2O–N).

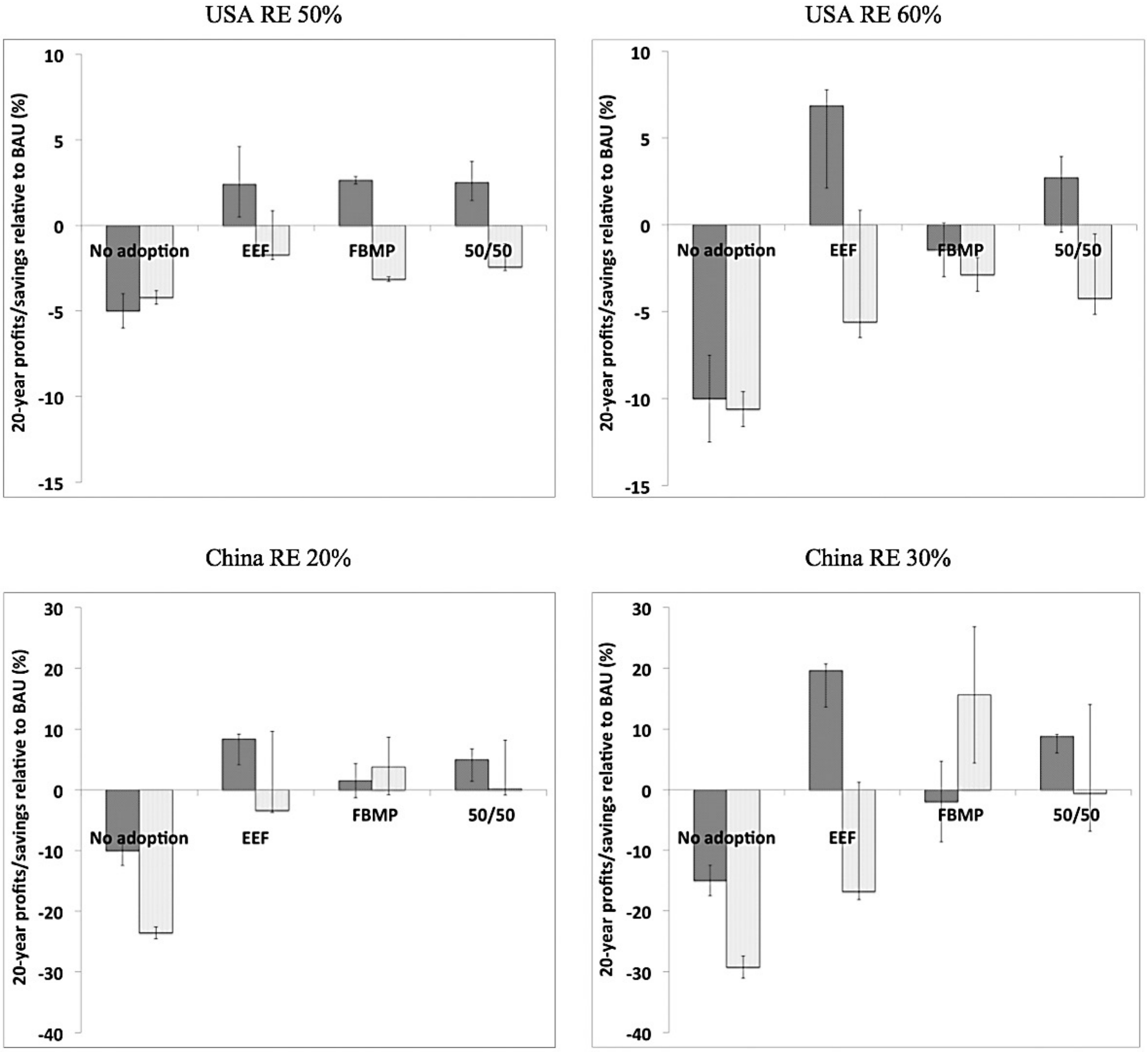

Fig. 3. Twenty-year industry profits (light gray bars) and farmer savings (dark gray bars) over the period 2015–2035 under the U.S. recovery efficiency (RE) 50%, U.S. RE 60%, China RE 20%, and China RE 30% targets for the no-adoption, 100% enhanced efficiency fertilizer (EEF), 100% fertilizer best management practice (FBMP), and 50/50 strategies relative to the business-as-usual (BAU) scenario. Error bars represent the uncertainty bounds for EEF price and production cost (this paper), FBMP prices (Winiwarter, personal communication, 2013), and yield losses (Vitosh et al., 1995).

Table 1. Absolute values of agricultural N pollution reduced over 20 yr in each N use efficiency scenario.

Nr† compound	United States		China	
	RE‡ 50%	RE 60%	RE 20%	RE 30%
	Tg N			
N_2O	0.1	0.2	0.3	0.6
NO_3^-	1.8	4.6	7.4	14.3
NO_x	0.3	0.8	1.2	2.4
NH_3	0.3	0.8	1.2	2.4
Totals	2.5	6.4	10.1	19.7

† Reactive nitrogen.

‡ Recovery efficiency.

China

Farmers and the Fertilizer Industry

The economic impacts of China's RE scenarios on farmers and the fertilizer industry are more pronounced compared with the United States given the more significant reductions in N inputs required to meet the RE targets. For example, the change in Chinese farmers' 20-yr fertilizer costs relative to BAU is projected to range from a 2% increase to a 20% reduction, depending on the implementation strategy. Similarly, the change in 20-yr fertilizer industry profits range from a 17 loss to a 16% gain relative to BAU (Fig. 3). Like the United States, the costs of "no adoption" as a response to the RE targets far outweigh the costs and/or benefits of all of the implementation strategies. Nevertheless, in contrast to the United States, it appears that a "sweet spot" does occur in certain situations using the current price/cost estimates for EEFs and FBMPs: farmers reduce costs and fertilizer industry increase profits relative to BAU using the 100% FBMP and 50/50 implementation strategies in the RE 20% scenario.

Environment

Reductions in N pollution over 20 yr range from 10.1 Tg N in the RE 20% scenario to 19.7 Tg N in the RE 30% scenario (Table 1). Akin to the United States, the environmental benefits of achieving the RE targets ($21–40 billion) are considerably greater than the impacts on fertilizer industry profits (ranging from a loss of $2.9 billion to a gain of $2.7 billion over 20 yr depending on the implementation strategy) and farmer savings (ranging from a loss of $1.5 to a gain of $15 billion over 20 yr) (Fig. 4; Supplemental Table S6).

These results show that the "sweet spot" (i.e., where farmers save, industry profits, and the environment benefits) is achievable only in China according to our model (specifically, in the RE 20% scenario using the 50/50 and 100% FBMP implementation strategies). Perhaps the central reason for the "sweet spot" occurring only in China is the considerably greater potential for N application rate reductions from improved NUE in China compared with the United States. Over the past three decades, NUE has increased considerably in the U.S. corn sector, whereas it has decreased in China's corn sector (see Section 1 in the supplemental materials).

A clear implication of our analysis is that the prices and production costs of EEFs and FBMPs are critical in determining whether the fertilizer industry profits and farmers reduce their fertilizer costs. It is therefore important to understand whether there are price ranges for EEFs or FBMPs that could create a "sweet spot" where none currently exists. The following section attempts to identify these "sweet spot" ranges.

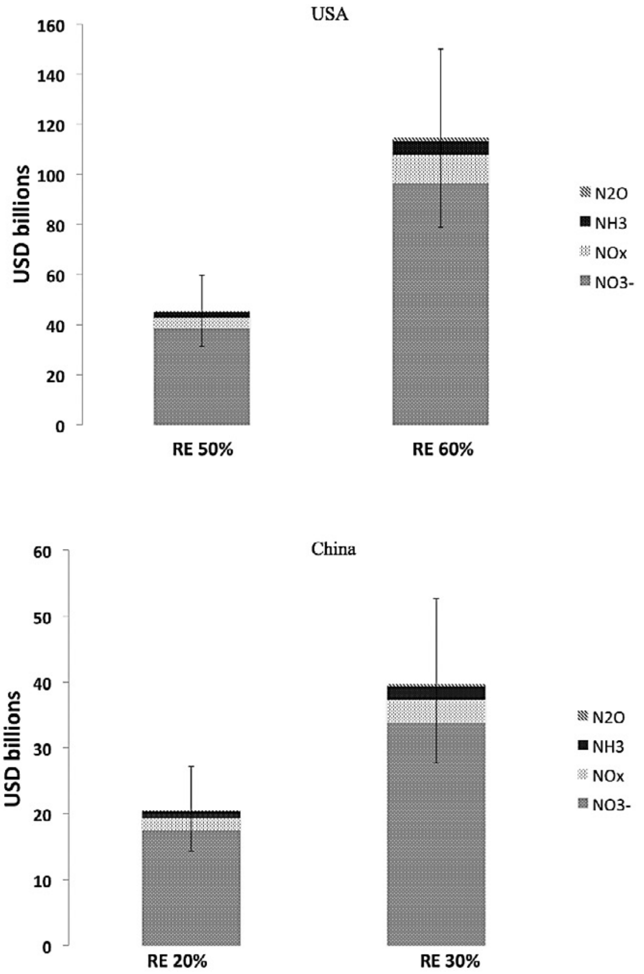

Fig. 4. Twenty-year environmental benefits over the period 2015–2035 of achieving the U.S. and China recovery efficiency (RE) targets relative to business-as-usual in terms of avoided economic damage (2005 USD billions). The uncertainty bars represent the range of damage cost estimates from Brink and van Grinsven (2011), Compton et al. (2011), and Gu et al. (2012).

"Sweet Spot" Ranges

United States

There is no potential for a "sweet spot" in either U.S. RE scenario using the 100% FBMP strategy, regardless of the values for FBMP price and cost of implementation: the FBMP price that would be high enough to generate industry profits leads to farmer losses, whereas the FBMP prices currently used in both scenarios lead to industry losses. Similarly, even if the FBMP cost of implementation in both scenarios is reduced to $0.00, industry would still be unable to make enough profit relative to BAU to offset the losses in revenue from reduced fertilizer sales. However, this should not lead to the conclusion that the provision of FBMPs in the United States is a completely unprofitable endeavor; it is simply less profitable than BAU. Moreover, as described in Section 5 of the supplemental materials, a significant portion of U.S. corn farmers already implement FBMPs; these are not only provided by several fertilizer companies but also by companies such as John Deere and Monsanto that could profit from the increased farmer demand for FBMPs stimulated by the RE targets while avoiding the brunt of the revenue losses from reduced fertilizer sales. Finally, although a fertilizer industry "sweet spot" range for the 100% FBMP strategy may not exist for the U.S. RE targets evaluated in this paper, it could well be that one exists for other more or less ambitious RE targets.

By contrast, there are a range of EEF price premiums that could lead to a "sweet spot" using the 100% EEF implementation strategy. In the RE 50% scenario, this price premium range is 33 to 52% above the price of traditional N fertilizer, with the lower bound marking the minimum value that would generate fertilizer industry profits equivalent to the BAU scenario and the upper bound the maximum value that would generate farmer fertilizer costs equivalent to the BAU scenario. Similarly, EEF price premiums of 37 to 60% would create a "sweet spot" in the RE 60% scenario (Fig. 5).

China

Figure 5 also shows the results for China of the same analysis conducted above for the United States. It demonstrates that in the RE 20% scenario, the "sweet spot" could be reached in the 100% EEF implementation strategy if the 2035 EEF price premium increased from 17 to 23–56% above the price of traditional fertilizer. If, by contrast, the 2035 EEF price premium remained at 17%, then the cost premium would have to decrease from 9 to 0–4% to ensure industry profitability.

Similarly, although the "sweet spot" is already achieved using the 100% FBMP strategy in the RE 20% scenario, the FBMP price of \$0.68 kg^{-1} N reduced could range from \$0.53 to \$0.77 kg^{-1} N reduced. Meanwhile, if the price per kg N reduced remained fixed, industry could still profit if the cost of implementing a FBMP ranged from \$0.00 to \$0.46 kg^{-1} N reduced (compared with the 2035 value of \$0.42 kg^{-1} N reduced).

A similar set of conclusions can be drawn from the RE 30% scenario: the EEF price premium would have to be in the range of 35 to 220% (as opposed to 15%) to create a "sweet spot." Meanwhile, the "sweet spot" range for FBMP price (\$0.55–\$0.77 kg^{-1} N reduced) is below the value currently used (\$0.82 kg^{-1} N reduced), and if prices remain fixed the implementation cost could range from \$0.00 to \$0.62 kg^{-1} N reduced and still generate industry profit relative to BAU.

Discussion

These results show that the potential for a "sweet spot" exists in both the United States and in China. However, obtaining a "sweet spot" in China is easier due to the current extensive overapplication of fertilizer, which creates a greater potential for farmers and the fertilizer industry to gain economically from improved N management. The key to achieving the "sweet spot" is finding a range of FBMP and EEF prices and costs that are high enough to offset reductions in fertilizer industry revenue while being affordable enough for farmers to reduce their fertilizer costs. Although it appears more likely across all the RE scenarios that farmers save rather than industry profits (particularly in the United States), the increasingly globalized market for N fertilizer means that industry profits from increased demand for EEFs and/or that FBMPs could potentially accrue across several national markets. For example, Agrium is the biggest supplier of N fertilizer to the United States and is increasing its business in China. Consequently, profit losses in one market could be offset by gains in another. Furthermore, although this study focuses on the average farmer, agricultural N pollution is primarily caused by farmers who significantly overfertilize (Williamson, 2011). The results of this study indicate that farmers that apply above-average amounts of N fertilizer have the most to gain from improving their NUE.

Finally, our results demonstrate that the environmental benefits of the various RE targets dwarf the economic impacts on the fertilizer industry and farmers. Consequently, if the social and environmental costs of N pollution shown in Supplemental Table S5 are realistic order-of-magnitude estimates, then society would stand to gain significantly from improved N management policies regardless of how the economic welfare of these two

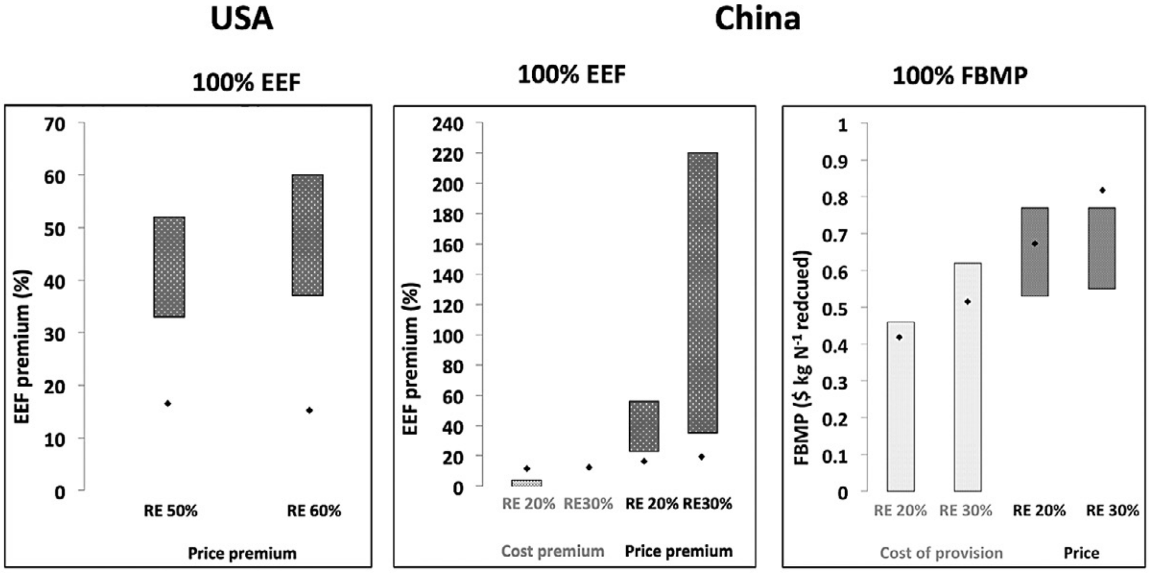

Fig. 5. The price and production cost ranges (represented by the various rectangles) for enhanced efficiency fertilizers (EEFs) or fertilizer best management practices (FBMPs) that could create a "sweet spot" in 2035 where none currently exist. The black diamonds represent the price and cost data from Supplemental Tables S2 and S3. Either EEF/FBMP production/provision costs are fixed at the levels described in Tables S2 and S3 while prices are shifted, or vice-versa (i.e., price is fixed while costs are shifted). These "sweet spot" ranges exist for most of the nitrogen use efficiency scenarios and implementation strategies, with the exception of the U.S. FBMP strategies and U.S. EEF production costs. The potential for a "sweet spot" range is much larger in China due to the current extensive overapplication of fertilizer, which creates a greater potential for farmers and the fertilizer industry to make economic gains from improved N management. RE, recovery efficiency.

major private stakeholders is affected. This dynamic suggests that viable policy options could include incentives for farmers and the fertilizer industry to increase the likelihood of their support for improved N management policies (Barrett, 2003). These could include subsidies for EEF R&D (to incentivize the fertilizer industry to accelerate their development and roll-out) and investments in technical infrastructure to educate farmers on the most appropriate and effective NUE practices and technologies and assist them in their deployment. These types of political "sweeteners" to stakeholders that might otherwise block policy initiatives could be justifiable given the considerable monetary benefits to society from reducing agricultural Nr pollution.

Future Research

Several next steps can expand on this research. First, it is important to improve the damage cost estimates of Nr pollution, starting from a set of common underlying assumptions. Second, it is important to test the "sweet spot" hypothesis in more countries (with a goal of global coverage) and on more crop systems (with a goal of all major fertilizer consumers) to determine where else farmers, fertilizer manufacturers, and the environment can simultaneously profit. Furthermore, it would be useful to combine the cost-benefit analysis of this study with a more detailed representation of agricultural N dynamics (e.g., Bouwman et al., 2011; Bodirsky et al., 2012) through integrated assessment modeling to provide a more coherent and holistic framework for policymakers to evaluate the environmental and economic impacts of various improved N management policy options. Such a modeling exercise could, for example, help policymakers better understand the environmental and economic trade-offs between EEFs and FBMPs for farmers and the fertilizer industry, another area in need of further study. Finally, it is important to consider the different policy mechanisms that could be used to implement NUE targets and how to ensure their successful implementation at the farm-scale. Although it is conceivable that overall targets on NUE could be set at the international level (Sutton et al., 2013), the implementation of these standards will depend on national and local circumstances.

Conclusions

Our study suggests that improved N management policies can be implemented in such a way that a "sweet spot" occurs where industry profits, farmers reduce their costs, and the environment benefits, although with a higher likelihood of one occurring in the corn sector in China than in the United States. The price and production costs of the NUE-improving technologies and practices are critical to achieving the "sweet spot." This study demonstrates the value of considering all major stakeholders, both public and private, when evaluating the economic impacts of improved N management policies and is the first to explicitly consider the fertilizer industry. Given the historical importance of industry's role in environmental governance, understanding the economic impacts of improved N management policies on the fertilizer industry is an important step forward in the evaluation of different policy options for addressing agricultural Nr pollution, and we hope future economic analyses of this kind will also include it.

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References

Ahrens, T.D., D.B. Lobell, J.I. Ortiz-Monasterio, Y. Li, and P.A. Matson. 2010. Narrowing the agronomic yield gap with improved nitrogen use efficiency: A modeling approach. Ecol. Appl. 20:91–100. doi:10.1890/08-0611.1

Alexandratos, N., and J. Bruinsma. 2012. World agriculture towards 2030/2050: The 2012 revision. ESA Working paper No. 12-03. FAO, Rome, Italy.

Archer, D.W., and A.D. Halvorson. 2010. Managing nitrogen fertilizer for economic returns and greenhouse gas reductions in irrigated cropping systems. Better Crops 94:4–5.

Aspinall, W. 2010. A route to more tractable expert advice. Nature 463:294–295. doi:10.1038/463294a

Avnery, S., D.L. Mauzerall, J. Liu, and L.W. Horowitz. 2011a. Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. Atmos. Environ. 45:2284–2296. doi:10.1016/j.atmosenv.2010.11.045

Avnery, S., D.L. Mauzerall, J. Liu, and L.W. Horowitz. 2011b. Global crop yield reductions due to surface ozone exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of ozone pollution. Atmos. Environ. 45:2297–2309. doi:10.1016/j.atmosenv.2011.01.002

Barrett, S. 2003. Environment & statecraft. Oxford Univ. Press, Oxford, UK.

Bates, J., N. Brophy, M. Harfoot, and J. Webb. 2009. Agriculture: Methane and nitrous oxide. Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC). AEA Technology, Oxon, UK.

Birch, M.B.L., B.M. Gramig, W.R. Moomaw, O.C. Doering III and C.J. Reeling. 2011. Why metrics matter: Evaluating policy choices for reactive nitrogen in the Chesapeake Bay watershed. Environ. Sci. Technol. 45:168–174.

Blaylock, A. 2013. Enhancing productivity and farmer profitability in broad-acre crops with controlled-release fertilizers. In: Third International Conference on Slow- and Controlled-Release and Stabilized Fertilizers, 12–13 Mar. 2013, Rio de Janeiro, Brazil.

Bodirsky, B.L., A. Popp, I. Weindl, J.P. Dietrich, S. Rolinski, L. Scheiffele, et al. 2012. N_2O emissions from the global agricultural nitrogen cycle: current state and future scenarios. Biogeosciences 9:4169–4197.

Bouwman, L., K.K. Goldewijk, K.W. Van der Hoek, A.H.W. Beusen, D.P. Van Vuuren, J. Willems, et al. 2011. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. Proc. Natl. Acad. Sci. USA 10:20882–20887.

Brink, C., and H. van Grinsven. 2011. Costs and benefits of nitrogen in the environment. In: M.A. Sutton, C.M. Howard, J.W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, et al., editors, European nitrogen assessment. Cambridge Univ. Press, Cambridge, UK.

Chen, X.P., F.S. Zhang, Z.L. Cui, F. Li, and J.L. Li. 2010. Optimizing soil nitrogen supply in the root zone to improve maize management. Soil Sci. Soc. Am. J. 74:1367–1373. doi:10.2136/sssaj2009.0227

Clapp, J. 2003. Transnational corporate interests and global environmental governance: Negotiating rules for agricultural biotechnology and chemicals. Env. Polit. 12:1–23. doi:10.1080/09644010412331308354

Compton, J.E., J.A. Harrison, R.L. Dennis, T.L. Greaver, B.H. Hill, S.J. Jordan, et al. 2011. Ecosystem services altered by human changes in the nitrogen cycle: A new perspective for US decision making. Ecol. Lett. 14:804–815. doi:10.1111/j.1461-0248.2011.01631.x

Cox, C. 2007. US agriculture conservation policy and programs: History, trends, and implications. In: K. Arha, T. Josling, D.A. Sumner, and B.H. Thompson, editors, US agricultural policy and the 2007 farm bill. Woods Institute for the Environment, Stanford University, Stanford, CA.

Cui, Z., X. Chen, Y. Mao, F. Zhang, Q. Sun, J. Schroder, et al. 2008. On-farm evaluation of the improved soil N_{min}–based nitrogen management for summer maize in north China plain. Agron. J. 100:517–525. doi:10.2134/agronj2007.0194

Del Grosso, S.J., T. Wirth, S.M. Ogle, and W.J. Parton. 2008. Estimating agricultural nitrous oxide emissions. Eos Trans. AGU 89:529–540. doi:10.1029/2008EO510001

DeRoos, A.J., M.H. Ward, C.F. Lynch, and K.P. Cantor. 2003. Nitrate in public water supplies and the risk of colon and rectum cancers. Epidemiology 14:640–649. doi:10.1097/01.ede.0000091605.01334.d3

Falkner, R. 2008. Business power and conflict in international environmental politics. Palgrave Macmillan, Basingtoke, UK.

FAPRI (Food and Agricultural Policy Research Institute–Iowa State University). 2011. World agricultural outlook database. http://www.fapri.iastate.edu/tools/outlook.aspx (accessed 15 Feb. 2013).

Fuchs, D. 2007. Business power in global governance. Lynne Rienner, Boulder, CO.

Galloway, J.N., J.D. Aber, J.W. Erisman, S.P. Seitzinger, R.W. Howarth, E.B. Cowling, and B.J. Cosby. 2003. Bioscience 53:341–356. doi:10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2

Grizzetti, B. 2011. Nitrogen as a threat to European water quality. In: M.A. Sutton, C.M. Howard, J.W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, et al., editors, European nitrogen assessment. Cambridge Univ. Press, Cambridge, UK.

Gruber, N., and J.N. Galloway. 2008. An Earth-system perspective of the global nitrogen cycle. Nature 451:293–296. doi:10.1038/nature06592

Gu, B., Y. Ge, Y. Ren, B. Xu, W. Luo, H. Jiang, et al. 2012. Atmospheric reactive nitrogen in China: Sources, recent trends, and damage costs. Environ. Sci. Technol. 46:9420–9427. doi:10.1021/es301446g

Huang, W. 2007. Impact of rising natural gas prices on US ammonia supply. WRS-0702. USDA Economic Research Service, Washington, DC.

IBISWorld. 2012. Global fertilizers and agricultural chemicals. IBISWorld Industry Report C1932-GL. IBISWorld, Melbourne, Australia

International Energy Agency. 2012. World energy outlook. International Energy Agency, Paris, France.

Intergovernmental Panel on Climate Change (IPCC). 2006. IPCC guidelines for national greenhouse gas inventories. Volume 4: Agriculture, forestry and other land use. IPCC, Hayama, Japan.

Johnston, J., and J. DiNardo. 1997. Univariate time-series modelling In: J. Johnston and J. DiNardo, editors, Econometric methods. McGraw-Hill, New York. p. 181–216.

Ju, X.-T., G.-X. Xing, X.-P. Chen, S.-L. Zhang, L.-J. Zhang, X.-J. Liu, et al. 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proc. Natl. Acad. Sci. USA 106:3041–3046. doi:10.1073/pnas.0813417106

Kanter, D., D.L. Mauzerall, A.R. Ravishankara, J.S. Daniel, R.W. Portmann, P.M. Grabiel, W.R. Moomaw, and J.N. Galloway. 2013. A post-Kyoto partner: Considering the stratospheric ozone regime as a tool to manage nitrous oxide. Proc. Natl. Acad. Sci. USA 110:4451–4457. doi:10.1073/pnas.1222231110

Kahrl, F., Y. Li, Y. Su, T. Tennigkeit, A. Wilkes, and J. Xu. 2010. Greenhouse gas emissions from nitrogen fertilizer use in China. Environ. Sci. Policy 13:688–694. doi:10.1016/j.envsci.2010.07.006

Kitchen, N.R., and K.W.T. Goulding. 2001. On-farm technologies and practices to improve nitrogen use efficiency. In: R.F. Follett and J.L. Hatfield, editors, Nitrogen in the environment: Sources, problems and management. Elsevier, Amsterdam, The Netherlands.

Kjellberg, L., S. Mironov, M. Priklonsky, L. Gandler, and S. Hartard. 2012. Global equity research fertilizers: Global fertilizers. Credit Suisse Securities Research and Analytics, Zürich, Switzerland.

Koch, B., R. Khosla, W.M. Frasier, D.G. Westfall, and D. Inman. 2004. Site specific management: Economic feasibility of variable-rate nitrogen application utilizing site-specific management zones. Agron. J. 96:1572–1580. doi:10.2134/agronj2004.1572

Laboski, C. 2006. Does it pay to use nitrification and urease inhibitors? Proc. Wisconsin Fertilizer, Aglime and Pest Management Conference 45:44–50.

Lammel, J. 2005. Cost of the different options available to the farmers: Current situation and prospects. IFA International Workshop on Enhanced-Efficiency Fertilizers, 28–30 June 2005, Frankfurt, Germany.

Levy, D.L., and P. Newell. 2005. Introduction: The business of global environmental governance; a neo-Gramscian approach to business in international environmental politics: An interdisciplinary, multilevel framework; business and international environmental governance: conclusions and implications. In: D.L. Levy and P. Newell, editors, The business of global environmental governance. MIT Press, Cambridge, MA.

Li, Y., W. Zhang, L. Ma, G. Huang, O. Oenema, F. Zhang, et al. 2013. An analysis of China's fertilizer policies: Impacts on the industry, food security, and the environment. J. Environ. Qual. 42:972–981. doi:10.2134/jeq2012.0465

Liu, M., Z. Yu, Y. Liu, and N.T. Konijn. 2006. Fertilizer requirements for wheat and maize in China: The QUEFTS approach. Nutr. Cycling Agroecosyst. 74:245–258. doi:10.1007/s10705-006-9002-5

McCann, L. and K.W. Easter. 2000. Estimates of public sector transaction costs in NRCS programs. J. Agric. Appl. Econ. 32:555–563.

Nelson, G.C., M.W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, and R. Robertson. 2010. Food security, farming, and climate change to 2050: Scenarios, results, policy options. International Food Policy Research Institute (IFPRI), Washington, DC.

Nordhaus, W.D. 2007. A review of the "Stern Review on the Economics of Climate Change." J. Econ. Lit. 45:686–702. doi:10.1257/jel.45.3.686

Organization for Economic Cooperation and Development–Food and Agriculture Organization (OECD–FAO). 2013. OECD–FAO agricultural outlook 2013–2022. OECD Publishing and FAO.

Ortiz-Monasterio, J.I., and W. Raun. 2007. Reduced nitrogen and improved farm income for irrigated spring wheat in the Yaqui Valley, Mexico, using sensor based nitrogen management. J. Agric. Sci. 145:215–222. doi:10.1017/S0021859607006995

Parson, E. 2003. Protecting the ozone layer: Science and strategy. Oxford Univ. Press, Oxford, UK.

PotashCorp. 2013. Overview of PotashCorp and its industry. http://www.potashcorp.com/overview/ (accessed 8 June 2013).

Rai, S. 2010. The global market outlook for agrochemicals to 2015: Competitive landscape, market size and company profiles. Business Insights, Warwickshire, UK.

Robertson, G.P., and P.M. Vitousek. 2009. Nitrogen in agriculture: Balancing the cost of an essential resource. Annu. Rev. Environ. Resour. 34:97–125. doi:10.1146/annurev.environ.032108.105046

Rockström, J., W. Steffen, K. Noone, Å. Persson, F.S. Chapin III, E.F. Lambin et al. 2009. A safe operating space for humanity. Nature 461:472:475.

Smil, V. 1999. Nitrogen in crop production: An account of global flows. Global Biogeochem. Cycles 13:647–662. doi:10.1029/1999GB900015

Sutton, M.A., A. Bleeker, C.M. Howard, M. Bekunda, B. Grizzeti, W. de Vries, et al. 2013. Our nutrient world: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. Centre for Ecology and Hydrology, Edinburgh, Scotland.

Trenkel, M.E. 2010. Slow- and controlled-release and stabilized fertilizers: An option for enhancing nutrient use efficiency in agriculture. International Fertilizer Industry Association, Paris, France.

UNEP. 2013. Drawing down N_2O to protect climate and the ozone layer: A UNEP synthesis report. United Nations Environment Programme, Nairobi, Kenya.

U.S Department of Agriculture Natural Resource Conservation Service (USDA–NRCS). 2003. Costs associated with development and implementation of comprehensive nutrient management plans: Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. USDA–NRCS, Washington, DC.

U.S. Energy Information Administration (USEIA). 2013. American energy outlook 2013 with projections to 2040. USEIA, Washington, DC.

USEPA. 2009. Expert Elicitation Task Force white paper. Science Policy Council, USEPA, Washington, DC.

U.S General Accounting Office (USGAO). 2003. Domestic nitrogen fertilizer production depends on natural gas availability and prices. Report to the ranking Democratic Member, Committee on Agriculture, Nutrition and Forestry, U.S. Senate, Washington, DC.

van Grinsven, H.J.M., A. Rabl, T.M. de Kok, and B. Grizzetti. 2010. Estimation of incidence and social cost of colon cancer due to nitrate in drinking water in the EU: A tentative cost–benefit assessment. Environ. Health 9:58. doi:10.1186/1476-069X-9-58

van Grinsven, H.J.M., M. Holland, B.H. Jacobsen, Z. Klimont, M.A. Sutton, and W. Jaap Willems. 2013. Costs and benefits of nitrogen for Europe and implications for mitigation. Environ. Sci. Technol. 47:3571–3579. doi:10.1021/es303804g

Venterea, R.T., A.D. Halvorson, N. Kitchen, M.A. Liebig, M.A. Cavigelli, S.J. Del Grosso, et al. 2012. Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems. Front. Ecol. Environ 10:562–570. doi:10.1890/120062

Vitosh, M.L., J.W. Johnson, and D.B. Mengel. 1995. Tri-state fertilizer recommendations for corn, soybeans, wheat and alfalfa. Extension Bulletin E-2567.

Williamson, J.M. 2011. The role of information and prices in the nitrogen fertilizer management decision: New evidence from the Agricultural Resource Management Survey. J. Agric. Resour. Econ. 36:552–572.

Winiwarter, W. 2005. The GAINS model for greenhouse gases, Version 1.0: Nitrous oxide (N_2O). Interim report IR-05-55. IIASA, Laxenburg, Austria.

World Bank. 2013a. Global economic prospects: Commodity market outlook–January 2013. http://siteresources.worldbank.org/INTPROSPECTS/Resources/334934-1304428586133/Commodities2013A_FullReport.pdf (accessed 26 Jan. 2013).

World Bank. 2013b. GNI per capita ranking, Atlas method and PPP based. http://data.worldbank.org/data-catalog/GNI-per-capita-Atlas-and-PPP-table (accessed 19 Aug. 2013).

Yara. 2012. Yara fertilizer industry handbook. http://www.yara.com/doc/57957_2012%20FIH%20Dec%20slides%20only.pdf (accessed 28 Jan. 2013).

Yara. 2013. Support tools. http://www.yara.com/products_services/fertilizers/support_services/support_tools/index.aspx (accessed 14 Mar. 2013).

Zhang, X., D.L. Mauzerall, E. Davidson, D. Kanter, and R. Cai. 2014. The economic and environmental consequences of implementing nitrogen-efficient technologies and management practices in agriculture. J. Environ. Qual. (in press). doi:10.2134/jeq2014.03.0129

Zhou, W. 2010. CO_2 emissions and mitigation potential in China's ammonia industry. Energy Policy 38:3701–3709. doi:10.1016/j.enpol.2010.02.048

Zhu, Z.L., and D.L. Chen. 2002. Nitrogen fertilizer use in China: Contributions to food production, impacts on the environment and best management strategies. Nutr. Cycling Agroecosyst. 63:117–127. doi:10.1023/A:1021107026067