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NITROUS OXIDE EMISSION REDUCTIONS FROM CUTTING EXCESSIVE NITROGEN FERTILIZER APPLICATIONS

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Nitrous Oxide Emission Reductions from Cutting Excessive Nitrogen Fertilizer Applications

Abstract

Farmers may choose to apply nitrogen fertilizer at a rate that exceeds the average ex post agronomically optimal rate when the yield response to nitrogen varies across growing seasons. Negative environmental consequences such as nitrous oxide (N_2O) emissions and/or water pollution can result when all the applied nitrogen is not needed by the crop. Here we consider a nonlinear market instrument targeting farmer's nitrogen use, and by solving for the optimal expected utility nitrogen reduction, we evaluate the induced N_2O emission reductions that are consistent with the instrument introduced. The market instrument is nonlinear because of the nonlinear relationship between N_2O and nitrogen application rates. Our simulations show that, by taking into account nonlinearity, payments will induce participation in the program and will have a significant impact on both expected and actual N_2O emissions without significantly harming expected or actual yields. Failure to consider this nonlinearity would deviate the attention away from N_2O pollution because it would require large N reductions (and crop yields) to achieve equivalent N_2O abatement. We also show the beginning-of-season probability distribution of emission reductions induced by this incentive scheme.

Key words: carbon offsets, nitrogen fertilizer, nitrous oxide, pollution, uncertainty.

Resumen

Los productores agrícolas pueden optar por aplicar fertilizantes nitrogeandos a una tasa que supera la tasa media a-posteriori agronómicamente óptima cuando la respuesta del rendimiento a nitrógeno varía en cada campaña. Pueden existir consecuencias ambientales negativas como las emisiones de óxido nitroso (N_2O) y/o la contaminación del agua cuando todo el nitrógeno aplicado no es utilizado por el cultivo. En este trabajo consideramos un instrumento de mercado no lineal dirigido el uso del nitrógeno en agricultura, y encontramos la reducción óptima que maximiza la utilidad esperada del productor, y luego evaluamos las reducciones de las emisiones de N_2O inducidas que son consistentes con el instrumento planteado. El instrumento de mercado es no lineal debido a la relación no lineal entre N_2O y tasas de aplicación de nitrógeno. Nuestras simulaciones muestran que, teniendo en cuenta la no linealidad, los pagos inducirán la participación en el programa y tendrán un impacto significativo en las emisiones de N_2O esperados y reales sin penalizar significativamente los rendimientos esperados o reales. No considerar esta linealidad se desviaría la atención lejos de la contaminación de N_2O porque requeriría grandes reducciones de N (y rendimiento de los cultivos) para lograr una reducción de N_2O equivalente. También mostramos, al comienzo de la temporada, la distribución de probabilidad de las reducciones de emisiones inducidas por este sistema de incentivos.

Palabras clave: carbon offsets, fertilizante nitrogenado, óxido nitroso, contaminación, incertidumbre.

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Introduction

When yield response to nitrogen (N) fertilizer varies across growing seasons, farmers may choose to increase their application rates to limit the chance that N will be a limiting nutrient (Babcock 1992; Sheriff 2005). When such behavior occurs, the years in which N is not limiting may cause negative environmental effects, such as volatilization of nitrous oxide (N_2O), water pollution, and other indirect effects on human health (Townsend et al. 2003; Galloway et al. 2008).

The extent to which yield response to N varies depends on complex interactions between soil mineralization rates, application rates, precipitation and rainfall (Li, Narayanan, and Harriss 1996). In the United States seven states have adopted a system named MRTN (maximum return to nitrogen). This system makes recommendations based on corn and fertilizer prices, on many years of yield response data, and on the fact that recommended rates are independent of climate because of soil mineralization responses (in drier years less N is mineralized from soil organic matter and in wetter years, more, making up for N not supplied by N fertilizer). The objective of the system is to limit N applications that do not result in yield response. One of the states that have adopted this system, Minnesota, recommends a range of N applications rates and includes this advice to producers: "A producer who is risk adverse (sic) and cannot tolerate risk associated with less-than-maximum yields in some years even though economic return to N may not always be the greatest may want to use the N rates near the high end of the acceptable range shown in Table 1." (Rhem et al., 2006; Kaiser et al., 2011).This type of advices is what motivates this analysis because in years in which the additional N is not needed by the crop it is lost to the environment. Thus over-application has a perceived but not actual pay-off in wet years because the shape of the yield response curve to N is relatively constant across a broad range of precipitation rates. We focus here on N_2O, a greenhouse gas (GHG) with global warming potential (GWP) 298 times higher than that of carbon dioxide (CO_2) over a 100-year time period.

Several studies using field level experimental data with at least three N rates applied have documented that low N_2O emissions occur when N is applied at or below the optimal crop requirement, but that higher emissions are consistent with N rates greater than that threshold. Hoben et al. (2011) using six rates between 0 and 225 kg N/ha shown that N_2O fluxes in

Michigan corn are best described by and exponential function. On a seven site-years field experiment, Ma et al. (2010) found that emissions doubled when fertilizer rose from 90 to 150 kg N/ha but corn yields increased only slightly. McSwiney and Robertson (2005) shown a nonlinear response of N_2O to N applications on continuous corn in Michigan using a nine points gradient between 0 and 291 kg N/ha. Izaurralde et al. (2004) in a 1999 experiment for wheat-fallow rotation at Saskatchewan, Canada found that plots fertilized at 110 kg N/ha significantly increased the N_2O emissions compared to those non-fertilized plots or fertilized with recommended 45 kg N/ha. At Broadbalk long-term experimental field in England, Yamulki et al. (1995) reported that N_2O emissions increased slowly with N applications until the optimum is reached (the fertilization level that crop requires) and then emissions rise sharply and in a nonlinear fashion.

Nonlinear N_2O response curves have also been reported using calibrated N_2O emissions models (Maggi et al. 2008; Del Grosso et al. 2006; Grant et al. 2006; and Li, Narayanan, and Harriss 1996), thorough literature reviews of peer-reviewed studies (Snyder et al. 2009; and Bouwman, Boumans, and Batjes 2002; FAO-IFA 2001), and conceptual models of N input saturation on ecosystems (Townsend et al. 2003).

This literature suggests that crops compete with N_2O-producing microbes for the use of N in soil, limiting N_2O production until crop N uptake has been satisfied. If the crop uses all available N in the soil, N_2O emissions will be low. Emissions will increase rapidly once the crop's N demand is satisfied. Consequently, a nonlinear function between N_2O emissions and N application rates seems an appropriate depiction of this relationship. More recently, based on peer-reviewed literature (Hoben et al., 2011; Millar et al., 2010), at least two carbon credit methodologies that reward farmers for reducing N applications base their payment structure on a nonlinear exponential response curve. These were adopted by the Verified Carbon Standard (Millar et al., 2013) and the American Carbon Registry (Millar et al., 2012), and is being evaluated for adoption by the Climate Action Reserve (CAR, 2013), allowing farmers to participate in voluntary carbon markets.[1]

[1] While the majority of the previous and recent evidence points towards a nonlinear curve, there is also evidence that for irrigated corn in Colorado N_2O response is highly linear up to 230 kg N/ha (Halvorson et al., 2009), and that N_2O emission factor decrease as N rate increases (Pelster et al., 2011).

The nonpoint source (NPS) nature of N_2O emissions implies that the most effective way to address the environmental consequences is by altering the use of the input that ultimately causes the pollution (Hansen 1998; Shortle and Abler 1997; Xepapadeas 1997; and Segerson 1988).

The main contribution of this article hinges upon the establishment of a connection between two aspects of the literature that have been, up until now, independently studied. The first one refers to the optimal fertilization decision when farmers face a market instrument targeting their N applications. The second is the quantification of N_2O emission reductions coming from cutting N fertilizer applications. In this article we calculate, for the first time, the magnitudes of N_2O emission reductions that are induced by a market instrument imposed on N fertilizer applications, for different CO_2 prices. These prices reflect the social value assigned to climate change. The yield and nonlinear N_2O response curves to N applications are calibrated to field-level data.

Considering the mentioned nonlinearity is crucial in at least two aspects throughout the paper: first, in designing a market instrument that transmits price signals to farmers that are consistent with their contribution to climate change and that prompt them to reduce N applications; and second, in driving the important result that modest fertilization reductions have large impacts in actual and expected N_2O emission reductions with minor crop yield penalties. Failure to consider this nonlinearity induces an underestimation of true emission abatement and discourages the application of N_2O policies. For example, a linear scheme that rewards by the same rate all N reductions (those which produce high emissions as well as those producing low emissions), would require large N reductions (and crop yield penalty) to achieve equivalent N_2O abatement. The response curves are also used to calculate the distribution of emission reductions at the beginning of the planting season produced by this market instrument.

Farmer's Optimization Problem

Consider a farmer who maximizes expected utility of per hectare profits by choosing the optimal level of N fertilizer application rate (in kilograms per hectare). The farmer's problem is

(1)

where is a strictly increasing and concave utility function, is the unknown output price at harvest time, is the concave yield response function affected by random weather during the growing season and dependent on a set of farm-specific characteristics (fertilizer type, soil type, tillage, and irrigation practices), and is the observed price of the fertilizer input[2]. Expectations ( ) are taken over the two random variables. Assuming, to facilitate the exposition, that is linear (i.e., risk neutrality) and that yield and output prices are independent random variables,[3] and denoting expected values with a bar, the first-order condition (FOC) is We denote its optimal solution as . Panel (a) of figure 1 shows the expected N_2O emissions associated with the optimal fertilizer application, and panel (b) shows the optimal at the intersection between the decreasing expected marginal value product curve and the constant observed marginal cost (point A).

Now suppose that society assigns a value to the environmental damage caused by farmer's N_2O emissions. The damage value is a function of the N rate and is calculated as , where is the quantity of N_2O emitted as a function of N and the set of farm-specific characteristics , is the exogenous market price of CO_2, and is the GWP equivalence between tons of CO_2 and kilograms of N_2O. In this regard, suppose there exists a regulatory agency that aims to incentivize farmers to reduce N fertilizer applications by, for example, distributing offsets (credits) for the carbon equivalent value of his direct and indirect[4] N_2O emission reductions.

The incentive payment structure accounts for the increasing and nonlinear relationship between N_2O emissions and N applications, for a given value of . In panel (a) of figure 1, the fertilizer rate (in kg N/ha) is plotted against expected emissions (in kg N_2O/ha/year). Based on

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[2] Conditioning on implies that optimal N rate, the solution to problem (1), is different if changes, making the problem potentially firm-specific. Therefore the model is general enough and contemplates as a special case the situation observed in practice where implementation of these type of schemes rely on protocols using a regional N2O-N response curve (Millar et al., 2013; Millar et al., 2012; and CAR, 2013).

[3] In the next section we remove the linearity and independence assumptions and solve the expected utility problem under risk aversion and correlated random deviates of yield and prices.

4 Indirect emissions consist of indirect N_2O emissions produced from atmospheric deposition of N volatilized, as well as N2O emissions produced from leaching and runoff of N, both as a result of N applications at the project site

this curve, we calculate the curve representing the market value of total damage, denoted by , as explained above.[5]

When farmers are paid for their emissions (or application) reductions with offsets, the optimization problem becomes the following:

(2)

where is the dollar payment received by the farmer for reducing nitrogen applications from to . Note that reductions are measured relative to , usually called the business-as-usual (BAU) or baseline rate, which is what this farmer would have applied in the absence of the incentive payment. With the mentioned per hectare payoff structure, the participating farmer receives a payment equal to zero when application equals (because these applications imply zero N_2O emission reductions), and the payment increases nonlinearly as the farmer reduces the applications. With our assumptions of linear utility and uncorrelated yield and output prices, the FOC is . The farmer's maximization is achieved when expected marginal value product equals marginal cost plus the value of emissions from a marginal unit of fertilizer applied, . The term increases the marginal cost of applying nitrogen (i.e., shifts the marginal damage curve up as shown in panel (b) of figure 1) because it represents the marginal dollar amount that the farmer forgoes for each kilogram of N that is applied. The solution, denoted as , is shown as point B, and the associated quantity of N_2O emissions is shown in panel (a). Therefore, given the decreasing marginal value product, the new optimality implies a reduction in N rates and N_2O emissions.

The marginal damage curve faced by a farmer under the program can shift for two reasons: (i) a change in the price of carbon, and (ii) a change in the emission function due to changes in for a given N application. In the first case, a higher price of carbon implies a higher opportunity cost of applying fertilizer, because the fertilizer application reductions are more valuable, so we should expect greater reductions in fertilizer applications (and emissions). In the second case, a different (such as fertilizer type, soil type, tillage, and

[5] While the implicit assumption is that social planner is risk neutral and maximizes over the expected payoff structure, we can alternatively assume a risk-averse social planner which values (positively) farmers' utility and (negatively) the uncertain emissions curve and that maximizes its expected utility by choosing the socially optimal payoff structure. Then this optimal structure is faced by farmers in their expected utility maximization problem.

irrigation practices) shifts . But also changes the marginal value product due to a shift in the production function ; therefore we cannot unambiguously say the direction of the fertilizer applications change. As a result we condition on the farm-specific parameter throughout the rest of the analysis.

This offset payment will induce the same N application reductions as a tax imposed on the purchases of the N input, provided the following conditions are met. (i) The tax structure, which according to panel (a) of figure 1 implies an increasing (progressive) tax rate, has a revenue curve (as a function of the N rate) that is equal to the total value damage curve . (ii) The tax rate has to adjust to the annual changes in the market price of carbon. A proof is available from the authors. Clearly, however, the distributive or welfare effects of each policy are different.

Outline of the Model

The offset structure takes into account two important factors. First, the input decision is made under uncertainty coming from both the stochastic production function and output prices. Second, the market value of N_2O emissions as a function of N fertilizer application rates and its first derivative are nondecreasing and nonlinear.

Emission reductions are measured relative to a BAU rate that we calculate as follows. At the beginning of the planting season a farmer maximizes expected utility of per hectare profits[6] by choosing the optimal nitrogen application rate, . He solves the following problem[7]:

(3)

where is the farmer's random profit, randomness coming from uncertain output prices and uncertain yields . Yields behave according to a conditional density function whose support is the non-negative closed interval , and representing the minimum and maximum yield possible, respectively. Output prices are governed by a probability

[6] In the previous section, for exposition, we assumed a farmer who maximizes under a linear utility. In what follows, we assume a utility that can accommodate different degrees of risk aversion. However results are very similar for different risk aversion levels.

[7] Conditioning parameters of and are omitted in the rest of the paper to save notation

density function where . Expectations ( ) are taken with respect to both random variables, and is a concave twice continuously differentiable utility function.

The FOC are . The solution is the farm-specific BAU rate which we denote by and is a function of and the set of parameters of the distributions and . We assume that the second derivative evaluated at is negative.

When the farmer faces the offset payment, the expected utility problem becomes

(4)

where .[8] Therefore, he maximizes a standard expected utility problem but incorporating the mentioned payoff structure. The FOC are

whose solution, denoted by , is a function of , , and the set of parameters of the function and the distributions and . We assume that the second derivative evaluated at is negative. With , we are able to analyze the consequences of introducing this nonlinear offset payment on the tradeoff between N rates and yields, and on the farmer's profitability.

The implementation of this program requires the farmer to report verified nitrogen application records and knowledge by the regulator of certain field characteristics (those included in parameter) to determine the baseline ( ) and actual ( ) application rates, and the payment function. Because farmers may have the incentive to misreport these values in order to claim more offsets verification and monitoring are an implementation challenge that is not new to the treatment of NPS pollution in agriculture.

While implementation of the program we describe is beyond the scope of this study, methodologies for quantification of N_2O emissions reduction in the U.S. North-Central region were recently designed and adopted by the Verified Carbon Standard (VCS) and the American Carbon Registry (ACR).[9] These "rate-based" protocols require the farmer to report not more than a verified crop history and fertilizer records. These are complemented by the so-called Best

[8] Similarly, to save notation we omit the conditioning parameter in

[9] The Climate Action Reserve (CAR) is currently evaluating its adoption.

Management Practices (BMP) in the use of fertilizers, such as the “Right Source-Rate-Time-Place (4R) Nutrient Stewardship” proposed by the International Plant Nutrition Institute (IPNI 2011) and the Nutrient BMP Endorsement for Crop Revenue Coverage Insurance (USDA-RMA 2003), which would reduce uncertainty about on-farm practices while simultaneously contributing to reduce N application rates. These consists of using ammonium-based fertilizers, slow/controlled release fertilizers, or inhibitors (right source); injected or band applications (right place); split applications in spring, and fall applications only if slow/controlled released fertilizers or inhibitors are used (right time); and applications based on field variability requirements and nitrogen balance (right rate) all overviewed by professional advisor.

Moreover, and regarding the payoff function, these N_2O reduction protocols simplify the implementation of the scheme by relying on a N_2O-N response curve that is extrapolated for the U.S. North-Central region and use it to calculate emissions reductions for any farmer voluntary enrolled from that region (Millar et al., 2013; Millar et al., 2012; and CAR, 2013).

Other initiative, which is more information intensive, has also been introduced in Alberta, Canada, and allows farmers to earn carbon credits for their quantifiable and verifiable N application reductions (Government of Alberta, 2010; CFI, 2011).

The Simulation Exercise

We assume that a farmer owns one hectare of land, plants it on a continuous corn rotation, and evaluates the decision to participate in the offset program to reduce N_2O emissions. The farmer solves the expected utility model described above. There exists an environmental regulatory agency that oversees the offset program and distributes carbon credits for N_2O emission reductions, reductions measured relative to the farm-specific BAU nitrogen rate .

N_2O Emissions and the N Application Rate

As mentioned above, we employ the nonlinear exponential emissions curve as a function of N rates used in the protocols for quantification of emissions reduction (Hoben et al., 2011; Millar et al., 2010) that was adopted by the VCS, ACR, and is under consideration by the CAR. The emissions curve is the following[10]:

(5)

This is consistent with the nonlinear relationship between emissions and the N rate shown in panel (a) of figure 1.

Assuming there exists an exogenous market price for CO_2 ( ), that is, GHG emissions are negatively valued by society, this emissions curve is used by the regulatory agency to construct the offset payment structure that rewards N reductions by the market value of their environmental damage. This value is , expressed in dollars per hectare. This nonlinear payment structure should give more efficient results because if the objective is to reward emissions reductions, a "flat" payoff to all application rates as suggested by IPCC-Tier 1[11] or a per unit nitrogen tax will not capture the implicit emissions behavior and thus will not provide correct signals to farmers. We compare both schemes in the results section.

It has to be noted that for a given N rate, different weather conditions will generate different levels of emissions. However, when determining the marginal payment structure, the regulator uses emissions at average weather conditions allowing the farmer to optimize under a known payment structure.[12] The optimization under an uncertain incentive scheme is treated by Segerson (1988). We present a sensitivity analysis of how results are driven by the estimation of this emissions curve using the standard error of the emissions curve stated in the mentioned protocols.[13] Also, we revise this assumption in the last section.

Estimation of a Conditional Yield Distribution

The yield response to nitrogen was estimated as a beta distribution with shape parameters and specified as a function of N application rates (see details in Online Resource 1). The beta distribution correctly describes the non-symmetric historical behavior of yields with respect to

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[10] The value of in , omitted to ease notation, is set at the average over the firms' values in the sample representative of the North-Central region.

[11] The Intergovernmental Panel on Climate Change (IPCC) assumes that N_2O emissions are a constant proportion of 1.00 +/- 1% of N applications (IPCC, 2006).

[12] The rationale of this assumption is that if we average a farmer's emission reductions over several years, they will be consistent with the incentive payment received in each year.

[13] The standard error of the emissions curve is:

factors that are unobserved at the beginning of the planting season (such as weather or pests). To estimate the production function we used 600 observations collected from field-plot experiments on continuous corn conducted between 1987 and 1991 on four different farms located in widely dispersed locations across Iowa. [14] Yields were updated to 2010 levels using a proportional yield adjustment based on Iowa corn yield growth. For any given N application rate, we can draw yield random deviates distributed beta.

Simulation of Correlated Yields and Price Draws

The optimization problem is to maximize expected utility of profits, where uncertainty comes from both random yields and random output prices. Random corn prices were generated assuming a lognormal distribution (see details in Online Resource 1). Given that the percentage change of commodity prices can be approximated by a normal distribution, the variable in levels (the commodity price) is lognormally distributed (Hull 2009, p. 271). We remove the independence assumption between corn prices and yields of the previous section by generating correlated draws from these two distributions (Johnson and Tenenbein 1981).[15]

Maximization of Expected Utility of Profits

First, we solve the case where emission are not valued by society, i.e. the BAU case with solution denoted as). To this end, we generate R=1000 random draws of correlated yields and corn prices and use a line-search algorithm to find a value of N that maximizes the expression:

$$- \qquad (6)$$

where and are the r^{th} draw of yield and corn prices, respectively; is a known price of nitrogen; and is assumed to be a constant absolute risk aversion (CARA) utility function of the form , where — is the coefficient of absolute risk aversion. The risk aversion coefficient was set as a value consistent with a risk premium equal to 0%, 25%, and

[14] Conclusions are conditional on the representativeness of this dataset of Iowa agronomic and weather conditions.

[15] We selected two levels of correlation; one negative based on historical observed correlation between corn yields and prices, and one positive for sensitivity analysis purposes. Negative correlation would exist because when corn prices increase, farmers have the incentive to plant more corn, substituting land away from other uses. If that new corn land is of lower productivity, we can expect a yield decrease. However, positive correlation might occur if higher prices induce changes in management practices with the objective of obtaining higher yields (using high-yielding seeds, higher seed density, different type of fertilizers and/or herbicides).

50% of the standard deviation of profits (Babcock, Choi, and Feinerman 1993; Babcock and Hennessy 1996; Hennessy, Babcock, and Hayes 1997).[16] As this percentage increases, the individual is willing to pay more money to avoid the risk, implying a more risk-averse agent.

We then solve the problem when emissions are negatively valued. The farmer takes as given the level of , , and the payoff structure , and maximizes the expected utility of profits conditional on R correlated draws of yields and corn prices. Then, the expression to be maximized by the farmer is

$$- \qquad (7)$$

We again use a line-search algorithm to find the maximum and denote the solution as . With and , we can find the nitrogen application reduction, and also the payment the farmer receives from the program.

Simulation Results for Nitrogen Application Rate

We present in table I results of the expected utility optimal application rate induced by participating in the offset program ( ), the BAU nitrogen application rate ( ), the reduction of N applied, the yield loss for applying less N, the incentive payment received by the farmer, and the change in the farmer's profits due to participation. We use carbon prices of \$15, \$30, and \$45 per ton of CO_2e, and various risk-aversion coefficients and price-yield correlations.[17]

Table I. Results of the N_2O Emissions Reductions Incentive Program (per hectare)

Carbon Price, = \$15/ton CO_2						
RP (%)	**(kg)**	**(kg)**	**N reduct.**	**Yield loss(%)**	**\$ payoff**	**increase**
~0	232	237	4.47	0.17	0.76	0.39
25	230	235	4.84	0.20	0.81	0.41
50	227	233	5.33	0.24	0.88	0.45
Carbon Price, = \$30/ton CO_2						
RP (%)	**(kg)**	**(kg)**	**N reduct.**	**Yield loss(%)**	**\$ payoff**	**increase**
~0	228	237	8.61	0.36	2.89	1.50

[16] The risk premium (RP) is the dollar amount an individual is willing to pay to avoid a risky bet and receive a certain profit. For our utility function, the risk premium is found to be — .

[17] Throughout the estimation we assumed a nitrogen price of \$722/ton N, equivalent to \$0.44/lb N suggested by Iowa State University Extension Services for continuous corn (Duffy, 2014).

25	226	235	9.30	0.42	3.07	1.59
50	222	233	10.20	0.50	3.31	1.72

Carbon Price, = \$45/ton CO_2

RP (%)	(kg)	(kg)	N reduct.	Yield loss(%)	$ payoff	increase
~0	224	237	12.46	0.55	6.18	3.25
25	221	235	13.44	0.64	6.56	3.46
50	218	233	14.71	0.76	7.04	3.73

Notes: Risk premium (RP) is the % of the standard deviation of profits. The corn price is \$196.57/ton, and the N price is \$722/ton N. Yield and corn price correlation = -0.30.

With a carbon price of \$30/ton of CO_2e, a participating farmer whose absolute risk-aversion coefficient is consistent with a risk premium equal to 25% of the standard deviation of profits optimally reduces his nitrogen applications by 9.30 kg/ha for participating in the program and obtains an incentive payment of \$3.07 per hectare. The increase in profits is \$1.59 per hectare because lower fertilizer costs are offset by a yield reduction. However, yield penalty is less than 0.5% while the incentive program induces N rate reductions of 4% and expected N_2O emission reductions of more than 6%.

Per ha N rate reduction obviously depends on farmer's starting point or BAU rate. It is worth mentioning that the obtained as an optimal solution from the model is within the recommended interval of N rates from Extension Services; [18] therefore in the real world, N reductions and payments could be larger for those farmers choosing N rates on the far right-end of the interval.

Because results are driven by the estimation of the nonlinear response curve of N_2O emissions to N applications, , i.e. the steepest the slope the highest the payment the farmers receives per unit of N reduced, we conduct a series of sensitivity analysis. Firstly, we use an estimated emissions curve that is approximately 2 standard deviations from equation (5); the curves are given by the following expressions: . With at \$30, the risk premium at 25%, and the emissions curve at the upper extreme of the interval, a farmer optimally reduces N applications by 13 kg/ha and receives a payment as high as \$6.45/ha with an yield penalty of only 0.6%; however in the lower extreme N reduction is 5 kg/ha and the incentive payment is \$0.20/ha.

[18] Iowa State University Extension Services using the MRTN-based Corn Nitrogen Rate Calculator recommends for Iowa and for corn and N prices used in this analysis, N application rates between 202 and 231 kg/ha (ISU Extension, 2014).

Secondly, we present results using an alternative dataset of pairs of N_2O emissions and N application rates to estimate the emissions curve, in (5). Data come from more than 20 studies based on corn field experiments conducted in the northern U.S. and Canada (Rochette et al., 2008; Grant et al., 2006; Li, Narayanan, and Harriss, 1996; Bouwman, 1996; Thornton and Valente, 1996). We estimate a cubic emissions curve by Ordinary Least Squares that controls for soil type and tillage, and adds a time trend (see Supplementary Online Materials). Farmers optimally reduce N applications by 17 kg/ha (7%) receiving an incentive payment of $11.31/ha and a yield reduction of 0.80%. The difference with the above results hinges upon the slope of this estimated emissions curve evaluated at the optimal rate which is equal to 0.043 versus the 0.025 of equation (5). Therefore, the high dependence of results on the estimated emissions curve calls the attention and highlights the importance of research on this issue.

On the other hand, farmer's risk preferences have little influence on final results. For levels ranging from risk neutrality to high levels of risk aversion, farmer's optimal N application reductions are very similar, as shown the second column of table I. One of the reasons relies on the concept of "apparent risk aversion" termed by Taylor (1986). He shows that a progressive tax makes the objective function more concave making the individual seem more risk-averse. In our case, with a progressive incentive, the concavity of the objective function is in part offset by the convexity of the progressive instrument, implying an "apparently less" risk-averse individual. [19]
Estimation results are also invariant to the production function estimated. An alternative set of results is derived using data on continuous-corn yields and N applications based on experimental plots from ISU Extension (2014). In the case of a $30/ton of CO_2e, a farmer whose absolute risk-aversion coefficient is consistent with a risk premium equal to 25% of the standard deviation of profits, optimal reduction of N applications are 11.22 kg/ha receiving an incentive payment of $3.22/ha. Also, the yield penalty is less than 0.5% but N applications are reduced by 5% and expected N_2O emissions are reduced by 6.5%.

Estimation of a Distribution of Emission Reductions

While the incentive program pays for expected N_2O emission reductions computed at the beginning of the period actual end-of-season emission reductions, for a given N application

[19] We solved the model with a positive correlation (=0.30), and results were very similar.

reduction, depend on random weather (rainfall and temperature in our particular case).. Once optimal and BAU N application rates are known, and especially ( ), we seek to document how disperse, around their expected value, end-of-period emission reductions effectively are. We do this by simulating random weather around annual N_2O emissions reductions.[20]

Distribution of Rainfall and Temperature

To simulate random weather, we fit nonparametric probability density functions to Iowa rainfall and temperature time series (1895-2008) from the National Climate Center at the National Oceanic and Atmospheric Administration (see details in Online Resource 1). Rainfall is the total annual precipitation for the state and is measured in centimeters per year (cm/yr).[21] Temperature is the annual average temperature for the state measured in degrees Celsius. Random draws were generated from both densities.

Weather Effects on N_2O Emissions

Based on our data collection on applications of N fertilizer and N_2O emissions, we estimate a response curve using the following regression model: .[22] Given that data from these studies covered different years, we assume that the fitted curve represents the behavior of emissions for average weather conditions. From this curve we calculate the levels of emissions at and . The effects of precipitation and temperature on N_2O emissions are obtained by running the Denitrification-Decomposition (DNDC) model calibrated for a continuous corn rotation in Iowa (Li, Narayanan, and Harriss 1996) with different N application rates. According to this model, per-hectare emissions decrease (increase) as annual precipitation (average temperature) rises (see details in Online Resources 1).

With these functions we obtain the level of emission reduction induced by the optimal N application reduction for each draw of the weather variables.

[20] For this simulation we select the scenario of = 30, RP = 0.25 and = -0.30.
[21] One inch of rain equals 2.5 cm.
[22] Not restricting the response curve for values of N less than does not affect the results because the portion of interest of the curve is to the right of .

Simulation Results for the Expected Reduction in Emissions

Emissions in N2O-N are converted to kilograms of carbon dioxide equivalent (kg CO_2e) by the formula: .[23] Average emissions at the BAU N rate are 1,623 kg of CO_2e ha/yr. Results show that for random precipitation but holding temperature at the average, average emission reductions are 121 kg of CO_2e, ranging between 93 and 178 (see figure 2, panel a).[24] The particular shape of this distribution is associated with the behavior of emissions as precipitation changes. The dollar value of the average emission reduction is \$3.64 per hectare, which is comparable to the \$3.07 received by the farmer. This suggests that the nonlinear offset program provides the correct price signals to farmers.[25]

The distribution of N_2O emission reductions as affected by random temperature shown in figure 2 panel b also has a shape determined by how emissions are affected by temperature. Average emissions are 103 kg of CO_2e per hectare per year, ranging between 97 and 137. Its dollar value is \$3.08.

These levels of N_2O emission reductions driven by the nonlinear payoff scheme, are higher than those if we were to consider a linear payoff structure such as that proposed by the IPCC Tier-1, where the N_2O response to N is approximated by a linear curve with a slope of 0.0125. In the \$30 carbon price scenario, a participating farmer would reduce N applications by 4 kg N/ha (from 235 to 231), receiving a payment of about \$0.58/ha. Or in order to make a comparable emission reduction of 121 kg of CO_2e (that in the nonlinear scheme is achieved by an N application reduction of 9.30 kg/ha, and a yield penalty of 0.42%), under this linear scheme, farmers would inadvertently have to reduce applications by 22 kg/ha, inducing a yield penalty of 2%).

To show how much these emission reductions represent, consider first that an approximation of the continuous corn area in Iowa in 2013 was about 1.9 million hectares. Then, using results for random rainfall and assuming that all Iowa continuous corn farmers participate

[23] The coefficient (44/28) converts N_2O-N to N_2O by the ratio of molecular weight of N_2O to the atomic weight of the two N_2O atoms in the N_2O molecule.

[24] The sensitivity analysis shows that in the case of the upper extreme of the 95% interval of the emission curve average per hectare emissions are 260 kg of CO_2e, and in the lower extreme, average per hectare emissions are 230 kg of CO_2e.

[25] The difference arises because, at the optimum, the slope of the emissions curve used by the regulatory agency, 0.025, is slightly lower than that obtained with the interpolation, 0.028.

in the incentive program, we get a reduction of about 228,000 ton CO_2e. The EPA Inventory of GHG for 2009 (U.S. EPA 2011) calculates N_2O emissions from the application of synthetic fertilizers on U.S. cropland and grassland at 40.8 million tons of CO_2e. Therefore, Iowa reductions based only on 2013 continuous corn would have been 0.55% of the total emissions from the application of synthetic fertilizer on U.S. cropland and grassland. Given that continuous corn rotation represents only about 33% of total Iowa corn in 2013, N_2O reductions from other rotations such as corn-soybeans might also be significant.

Conclusions

The overapplication of nitrogen by corn growers, while optimal from an ex ante perspective, has negative environmental consequences. In this article, we document the N_2O emission reductions that are consistent with a market instrument imposed on nitrogen fertilizer applications in order to induce a lower use of nutrients. The instrument targets the nitrogen applications because of the NPS nature of the emissions. We consider a farmer maximizing expected utility of per hectare profits and choosing the optimal nitrogen application rate. Reductions are measured relative to the farm-specific BAU nitrogen rate. We use a nonlinear payoff structure that is consistent with the nonlinear relationship between N_2O emissions and nitrogen application rates. This instrument is far more efficient than traditional linear schemes because it transmits price signals that are aligned with the true N_2O behavior and the ultimate objective of the program.

The key insight in the article is driven by the simulation results. These show that with a modest to medium carbon price of \$30 per ton of CO_2e, a farmer reduces his nitrogen applications by about 7% as a result of an offset payment of \$3.07 per hectare. The lower nitrogen induces only a minimal expected yield penalty (about 1%) because the program targets nitrogen applications that in most years are surplus relative to crop needs. Therefore, taking into account the mentioned nonlinearity, we find that the true impact on N_2O emission reductions is significant but yields are only slightly harmed. A linear scheme aiming to achieve the same N_2O emission reductions would inadvertently require an N application reduction of 10% with an associated yield penalty of 2%. Therefore, failure to consider this nonlinearity may render an N_2O emission reduction policy unattractive.

Results are robust to different levels of risk aversion which is due to the so-called " apparent risk-aversion".

We also present the dispersion of emission reductions induced by this market instrument that takes into account a priori unknown weather variables. We find that, for random rainfall and fixed temperature, N application reductions induce a distribution of emission reductions that averages 121 kg CO_2e per hectare, with a shape depending on how emissions respond to rainfall. For random temperature and fixed rainfall, the average reduction is 103 kg CO_2e per hectare.

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Figures

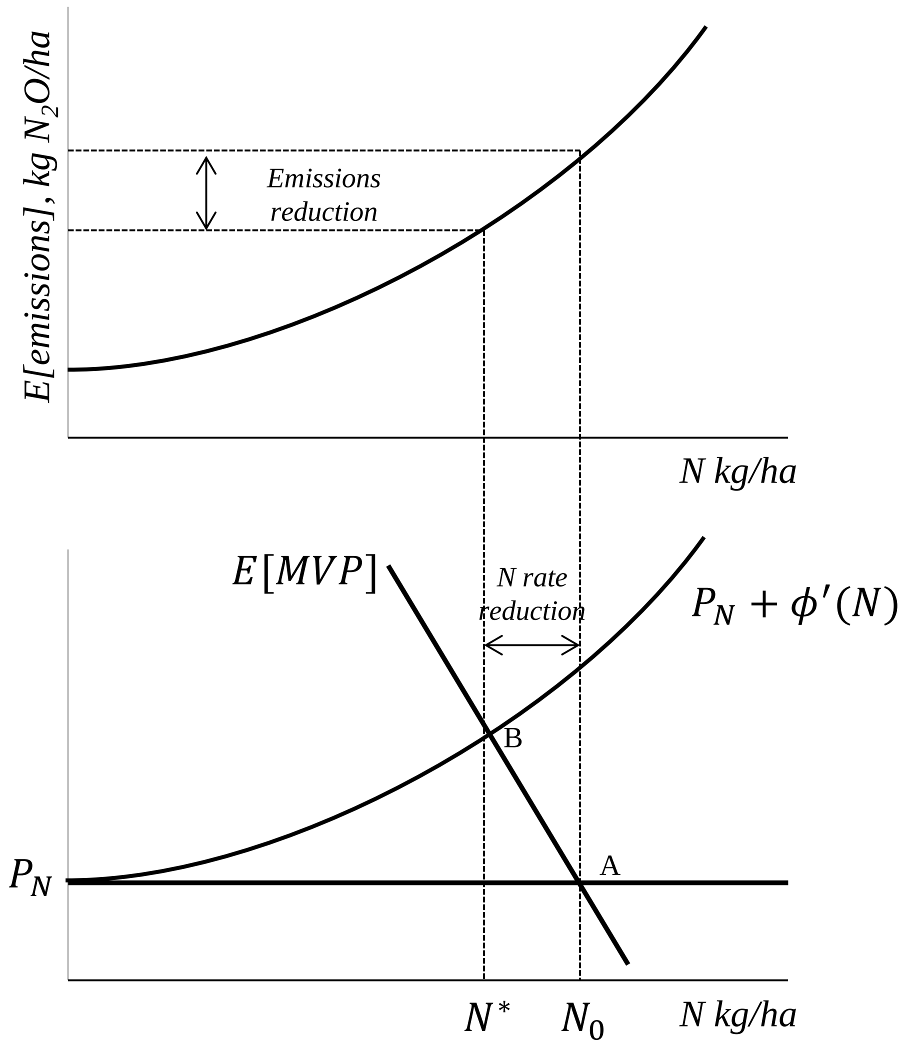

Figure 1. Panel (a) N_2O emissions as a nonlinear function of nitrogen rates, and N_2O emission reductions from the incentive program

Panel (b) Profit maximizing nitrogen application rates in the business-as-usual case (point A) and the case of N_2O emissions negatively valued by society (point B), and optimal nitrogen application reductions

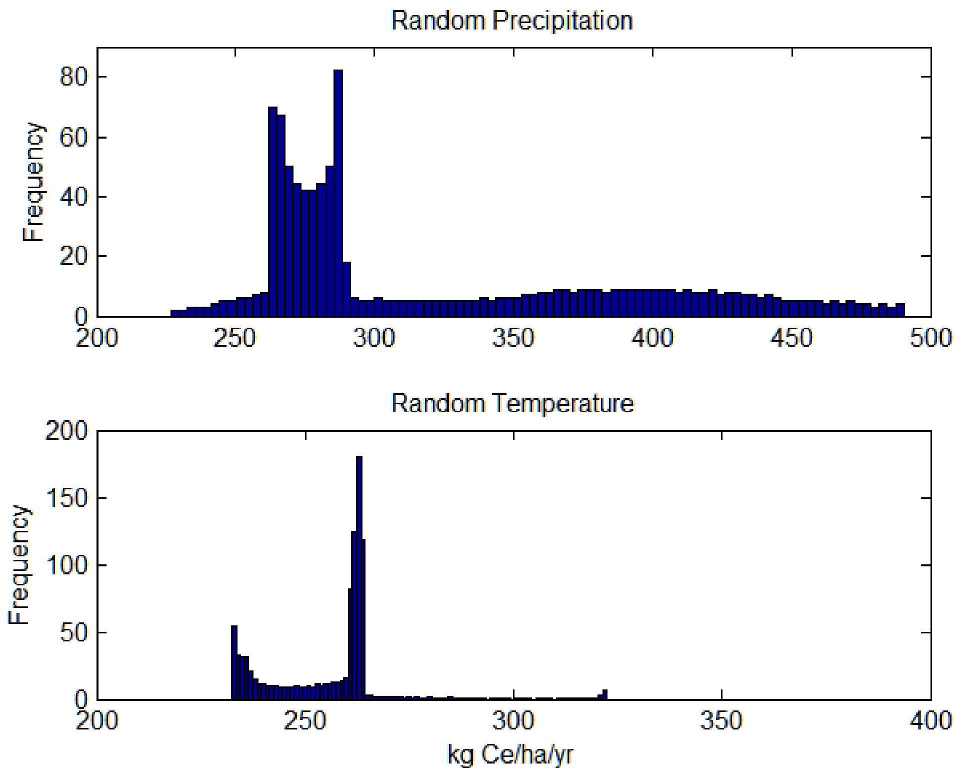

Figure 2. Histograms of N_2O emission reductions (kg of carbon equivalent per hectare) for random precipitation (panel a) and random temperature (panel b), induced by an optimal N application reduction of ( ) = 16.00 kg N/ha, when = \$30/ton CO_2