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Benefits of pollution monitoring technology for greenhouse gas offset markets

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Abstract

Environmental economists have shown that tradable emission permit markets can reduce the costs to society of pollution reduction. However, when emissions are difficult to monitor and verify, offset credits from pollution reductions may be subject to price discounts that reduce social welfare. In this paper, we estimate the extent to which social welfare could be improved by using new technology to increase the accuracy with which pollution flows from agricultural fields can be monitored. We use a hypothetical case study of a situation in which farmers can reduce nitrous oxide (N2O) emissions from Midwest agricultural land parcels and sell the resulting offset permits in a greenhouse gas tradable permit market. We simulate market outcomes with and without an inexpensive technology that increases the accuracy of emission estimates, reduces the discount to which agricultural offset permits are subject, and improves the performance of tradable permit system. We find that the benefits from such technology range as high as $138 for a 100 acre field if N2O emissions are an exponential function of nitrogen application rates. However, variation in the benefits to farmers of eliminating price discounts may mean efficient technology adoption is not uniform across space.

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1. Introduction

Environmental economists have long touted tradable emission permit markets as cost-effective tools for accomplishing pollution reduction goals (Crocker, 1966; Dales, 1968; Montgomery, 1972). However, the literature has recognized that these policy tools may work less efficiently in the face of market imperfections such as market power (Hahn, 1984) and high transaction costs (Stavins, 1995). In the case of tradable permits for non-point source emissions such as waterborne nitrate or greenhouse gas (GHG) fluxes, observability can pose a serious problem for the functioning of a tradable permit market. Industrial sources might want to be able to pay farmers for pollution offset credits generated by changes in farm activities that reduce net pollution flows from their fields. However, it can be very difficult for a buyer to be certain about the quantity of pollution reduction generated even by observable farmer behaviors. Such pollutant flows themselves are not directly observable with current monitoring technologies and the relationship between farmer actions and pollution generation typically depends in complex ways on continuously stochastic variables such as temperature and rainfall.

Uncertainty about pollution flows from agricultural sources subjects agricultural offsets to price discounts in tradable permit markets. Many markets for water-pollution permits effectively have such discounts by requiring point sources to trade with agricultural non-point sources at a trading ratio greater than one (Horan, 2001). Several papers (McCarl *et al*., 2003; Kim and McCarl, 2009) study the importance of uncertainty in markets for carbon offsets, finding that uncertainty does (and perhaps should) cause such offsets to be discounted at the Chicago Climate Exchange by about 15%. Kurkalova (2005) estimates that uncertainty in carbon sequestration outcomes in Iowan agriculture should yield a 9% price discount from an offset credit aggregator. The presence of such discounts will cause a tradable permit market to yield too little pollution reduction from agricultural sources relative to the cost-effective outcome, resulting in deadweight loss from misallocation of abatement among sources.

Engineers and computer scientists are working currently to develop new technologies to produce accurate real-time measurements of pollution fluxes from agricultural fields (Panayiotou *et al*., 2005; Montgomery *et al*., 2007; Mariño *et al*., 2008). Small sensors can be connected in wireless networks to provide data to computer programs which translate flows of raw data into information about pollution that could be used by land owners and regulators. However, even inexpensive sensors are not free, and the area to be monitored could be very large. One would not incur the cost of installing and maintaining such a monitoring network unless the benefit to society of doing so was at least as large as the cost. Some studies have found that measurement technologies and protocols would generate large efficiency gains in markets for agricultural soil carbon sequestration (Mooney *et al*., 2004; Kurkalova *et al*., 2004). However, such analysis has been limited to carbon. It is not clear the results apply to markets for other GHGs (such as methane (CH_4) or nitrous oxide (N_2O)) which could be subjects of tradable permit regimes, because different management strategies are needed to reduce those emissions.

In this paper, we estimate the extent to which social welfare could be improved by developing and employing new technology to increase the accuracy with which flows of N_2O emissions from agricultural fields can be monitored, and we demonstrate how that welfare improvement depends on the nature of the emission-generation process. We use a hypothetical case study of a situation in which farmers can reduce N_2O emissions from Midwest agricultural land parcels and sell the resulting offset permits in a GHG tradable permit market. We simulate market outcomes with and without technology that increases the accuracy of emission estimates, reduces the discount to which agricultural offset permits are subject, and improves the performance of tradable permit system. We find that the benefits from such technology are fairly modest, but range as high as $138 for a 100 acre field if N_2O emissions are an exponential function of nitrogen application rates.

2. Background

GHG emissions are of major environmental concern because they have been implicated as causes of anthropogenic climate change (IPCC, 2007). According to the Intergovernmental Panel on Climate Change (IPCC), major GHGs include carbon dioxide (CO_2), N_2O, CH_4, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride (SFl_6).

Cerri *et al*. (1996) find that agriculture is a major contributor of N_2O and CH_4 and CO_2, explaining approximately 13.5 percent of global N_2O and CH_4 emissions (IPCC, 2007). GHG flux reductions can be achieved by farmers through changes in crop management practices. Nevertheless, such changes typically need to be stimulated either by government policies or by creation of markets which give incentives for such reductions. Numerous papers have studied the economic potential for soil carbon sequestration in agricultural soils and explored the relative virtues of different policies to encourage sequestration (Stavins, 1999; Antle *et al*., 2001; McCarl and Schneider, 2001; Lewandrowski *et al*., 2004). Other work has studied reducing multiple types of GHG emissions from agriculture (Hyman *et al*., 2004; Brink *et al.*, 2005; De Cara *et al*., 2005; Golub *et al*., 2009; Vermont and De Cara, 2010).

N_2O emissions in the U.S. Midwest are affected heavily by the use of fertilizer nitrogen (N) in row crop agriculture; such emissions can be reduced significantly by changing fertilizer use rates. Numerous papers have documented a linear relationship between N and N_2O, leading the IPCC to use such a relationship in its integrated assessments (IPCC, 2007; Halvorson *et al,*. 2008). Other papers have argued that the relationship between N and N_2O is nonlinear; the nonlinearity arises because emissions rise rapidly when there is residual fertilizer not used for growth by the crop (McSwiney and Robertson, 2005). The literature on this subject recognizes that N_2O emissions from a specific field can be affected by factors such the crop which is grown (N absorption by the crop reduces emissions), climatic conditions, topography, tillage system, and the time of year at which the fertilizer is applied. For tractability (and because of data limitations) we abstract from a large number of factors that influence the exact quantity of N_2O emissions from a given amount of N fertilizer on a specific field. However, we use a relationship between N and N_2O estimated by Millar *et al.* (2010) which is tailored to conditions on soy-corn fields in the lower Midwest, and thus captures some specifics of N_2O generation from N fertilizer in a study area such as ours.

This paper carries out a case study of N_2O reduction policy on agricultural land parcels in the Upper Embarras Watershed (UEW). The UEW is located in East-Central Illinois, lying primarily in Champaign and Douglas counties. We use the boundary of this sub-watershed given by shape files from the USGS with hydrologic unit boundaries and codes.[1] We use a GIS dataset on land parcels provided by the Champaign County Development Services Office in Champaign, IL, and extract agricultural parcels in that county that lie within the UEW.[2] The database included information on parcel acreage and average productivity index (API), an important measure of soil quality. The final dataset contained observations on 1,361 parcels. Agriculture in this area is dominated by large fields devoted to corn/soybean rotations, and the soil is of very high quality. Rainfall is plentiful, so farmers in this area do not irrigate.

3. Analysis

In a well-functioning market for tradable emission permits, pollution sources will end up choosing emission levels such that their marginal costs of pollution reduction are equal to each other (if marginal costs vary between two sources, the high cost source will have an incentive to pay the low cost source to do some of its required abatement). Thus, total pollution reduction is accomplished at the smallest total cost to society. However, if uncertainty causes some sources to face a price that is lower than the price faced by other sources, cost-effectiveness will not be achieved. We use data on agriculture parcels in the UEW to develop a model that can simulate the response of farmers in the UEW to a hypothetical market for GHG permits into which they could sell offsets produced by reducing N_2O emissions from their fields. We simulate the functioning of such a market when offsets from these fields are subject to a discount because agricultural N_2O emissions are measured with high uncertainty. We then estimate the benefit to society of a new technology that reduces measurement uncertainty and improves the cost-effectiveness of the market outcome.

3.1 Estimation of marginal abatement cost curves

Environmental economic theory tells us that profit-maximizing farmers will choose N levels to reduce N_2O such that the cost of the last unit of pollution reduction (marginal abatement cost, or $MAC(N_2O)$) is equal to the price they can receive for a unit of reduction (or abatement). Thus, to predict farmer participation in a market for N_2O offset permits we need to estimate marginal abatement cost curves for acres of land in the different parcels in the watershed.

To do this, we observe that farmers make per acre profits that can be represented as quadratic functions of their rate of N use (Figure 1).

$$\Pi = \alpha + \beta_1 N + \beta_2 N^2 \tag{1}$$

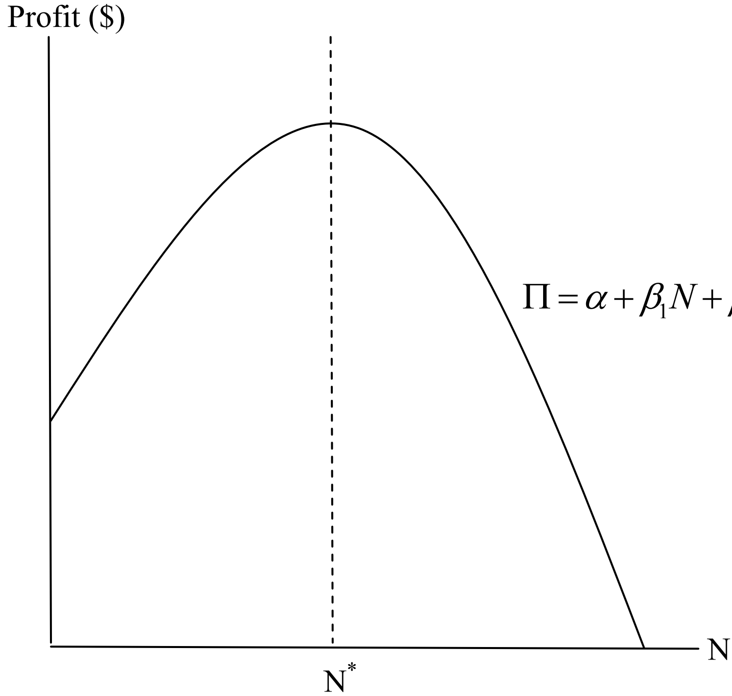
Profits rise with fertilizer use over a range of application rates, but too much fertilizer is both expensive and bad for crop growth. We assume that with no incentive to reduce N use, farmers will choose to apply fertilizer at the profit-maximizing rate N^*. This is consistent with a neo-classical approach to modeling decision makers. However, some research indicates that farmers apply more fertilizer than the recommended profit-maximizing rate because of distrust of recommendations, risk aversion, or complementarities among inputs (Sheriff, 2005). Future

[1] The UEW has HUC 10 code 0512011201.

[2] Invalid and inappropriate records were omitted (such as lots with zero acreage and negative farmland values).

research on this subject could adapt our basic model to different assumptions about farmer behavior to evaluate the effect on the model's results of phenomena that induce over-application.

Figure 1. Profit as a Function of Nitrogen Application



As discussed in Section 2, we model N_2O emissions caused by human behavior as an increasing function of N (Millar *et al*., 2010). That equation can be linear or nonlinear:

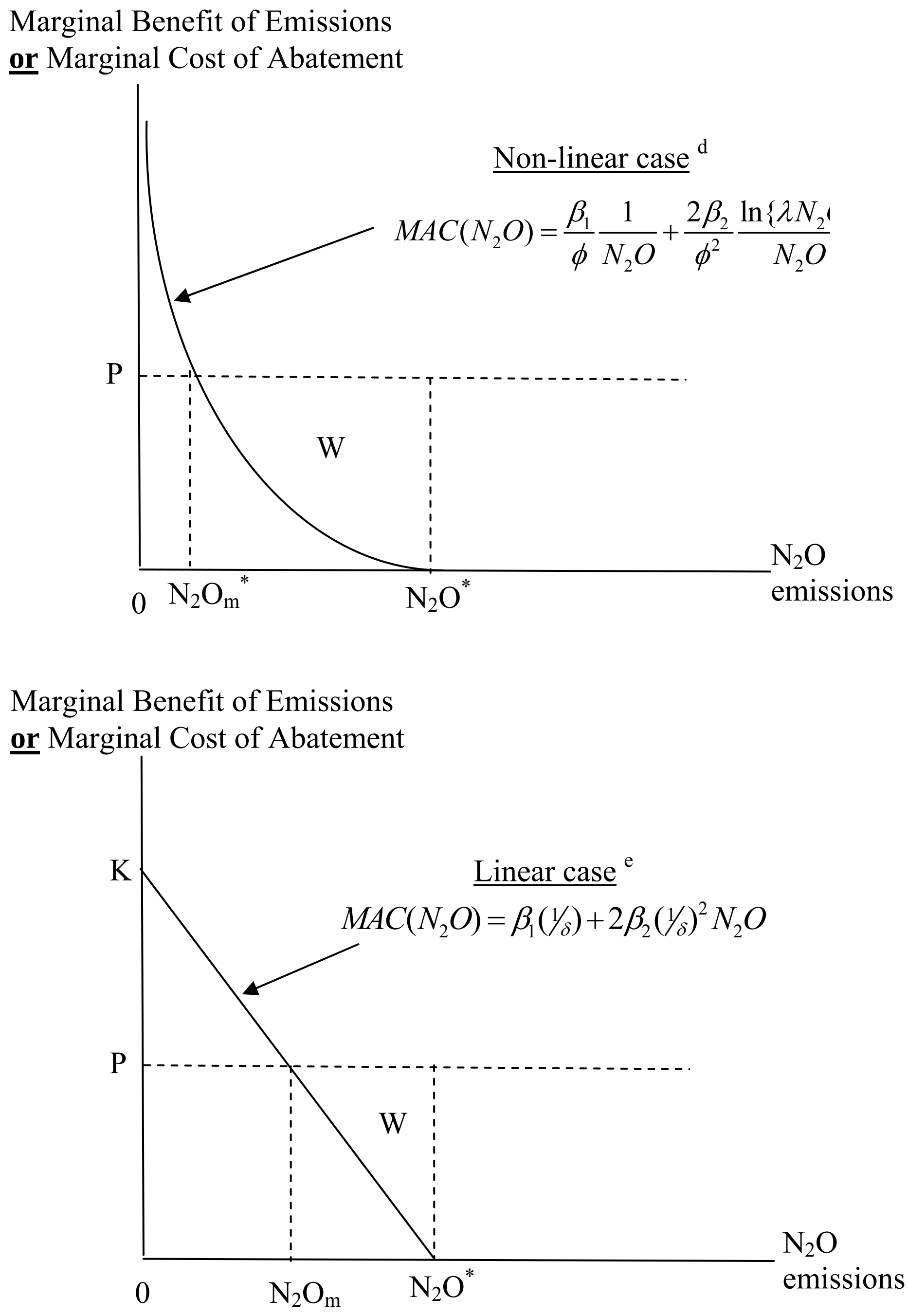
$$linear: \quad N_2O = \delta N \qquad \text{where } \delta = 4.684,^{3} \tag{2}$$

$$nonlinear: \quad N_2O = c\exp\{\phi N\} \text{ where } c = 298*(44/28), \phi = .0082. \tag{3}$$

Thus, there is a profit maximizing level of N_2O (N_2O^*) which is the amount of N_2O associated with a fertilizer application rate of N^*. These conditions imply that the marginal abatement cost curve for reducing N_2O from a field is a downward sloping line or curve where the marginal cost is equal to zero at N_2O^* (see Figure 2). The marginal abatement cost (MAC) of reducing a unit of N_2O emissions is equal to the foregone marginal benefit to the farmer of that unit. At the profit maximizing fertilizer application rate, the marginal contribution of fertilizer to profit is very small and thus the profit lost by cutting fertilizer (and hence N_2O emissions) is also very small. At low levels of fertilizer use, however, reducing fertilizer more has a large deleterious effect on crop yields and hence profit, and so the marginal cost of reducing N_2O emissions by one unit is high when emissions are already low.

[3] N_2O emissions in pounds of CO_2 equivalent emissions are $N_2O = (0.01 * N) * (44/28) * 298$. The molecular weight of N_2O is 44/28 and 298 is the global warming potential of N_2O (Millar et al., 2010).

Figure 2. Marginal Benefits of N_2O and Marginal Costs of N_2O Abatement [a,b,c]



[a] $\Pi = \alpha + \beta_1 N + \beta_2 N^2$. The MAC of reducing N_2O is the marginal benefit of that foregone unit.

[b] N_2O emissions are measured in units of CO_2-equivalent GHG emissions.

[c] Area W is the increase in social welfare from the sale of $N_2O_m^*$ offset credits.

[d] Nonlinear model assumes $N_2O = c\exp\{\phi N\}$ where $c = 298*(44/28), \lambda = 1/c, \phi = .0082$.

[e] Linear model assumes $N_2O = \delta N$ (δ = 4.684).

Table 1. Recommended Nitrogen Application Rates with Corresponding Expected Yields and Profits

Level	N rate[a,b,c] (lbs N/acre)	Corn Yield[a,b,c,d] (bushels/acre)	Profit[b,e] ($/acre)
Low	163.52	174.28	595.03
Profit maximizing	188.84	176.28	596.46
High	212.60	177.52	595.50

[a] The nitrogen recommendations are obtained from the Iowa State University Extension N rate calculator (http://extension.agron.iastate.edu/soilfertility/nrate.aspx). The profit-maximizing level of N is not typically equal to the yield maximizing level (Sawyer *et al*. 2006). The calculator also provides "high" and "low" recommended rates which are associated with profits no more than $1.00/acre lower than that associated with the profit maximizing level of N.

[b] We assume the price of corn is $3.63/bu and the price of N fertilizer is $0.23/lb. Source: Farm Decision Outreach Central, University of Illinois, http://www.farmdoc.illinois.edu.

[c] We assume a field with soybean/corn rotation and an API equal to 117.

[d] Yield is calculated from Sawyer (2006).

[e] Profit per acre is calculated as $\Pi = P_{corn}$*Yield – P_N*N rate.

We parameterize MAC curves like those shown in Figure 2 for agricultural parcels in the UEW by taking the following steps. First, we estimate the slope of a typical marginal cost curve for N reduction on soybean/corn rotation fields in Central Illinois by fitting a quadratic curve to estimates of profits for three different levels of fertilizer: low, profit-maximizing, and high (see Table 1). Equation (4) gives the resulting fitted equation:

$$\Pi = 524.8 + 0.7520 * N + (-0.001974) * N^2 . \tag{4}$$

Second, we estimate the manner in which N^* varies with soil quality as measured by the API. We use N^* levels recommended by a fertilizer-rate calculator[4] for three different API values that could obtain on farmland in Illinois to estimate an equation that predicts N^* for the value of API that obtains for parcel *i*. Equation (5) gives the result:

$$N_i^* = 304.8 + (-1.115) * API_i \tag{5}$$

This gives us a parcel specific marginal cost of reducing N, where the intercept N_i^* is given by Equation (5). We make the simplifying assumption that the slope of *MAC*(*N*) (that is, $2\beta_2$) is fixed across parcels, but its x-intercept N^* shifts with each parcel's API. Since $N^* = -\beta_1 / 2\beta_2$ then we define for each parcel $\beta_{1i} = -2\beta_2 N_i^*$.

[4] Source: The nitrogen recommendations are obtained from the Iowa State University Extension N rate calculator (http://extension.agron.iastate.edu/soilfertility/nrate.aspx). We assume soy/corn rotation and a price ratio of N to corn equal to 0.063.

Third, we use Equations (2) and (3) to derive marginal cost curves for reductions of N_2O emissions (in pounds of CO_2 equivalent GHG emissions) in the linear and nonlinear cases:

$$linear: \quad MAC_i(N_2O) = \beta_{1i}(1/\delta) + 2\beta_2(1/\delta)^2 N_2O \tag{6}$$

$$nonlinear: \quad MAC_i(N_2O) = \frac{\beta_{1i}}{\phi}\frac{1}{N_2O} + \frac{2\beta_2}{\phi^2}\frac{\ln\{\lambda N_2O\}}{N_2O}. \tag{7}$$

The result is a set of 1,361 pairs of marginal abatement cost curves, one pair for a representative acre of land on each parcel in the study area. In terms of N, those curves have the same slopes but their point of intercept with the horizontal axis varies with soil quality on the parcel. When N_2O is a linear function of N, the MAC curves in terms of N_2O still have identical slopes, but that is not true when N translates into N_2O in a nonlinear fashion.

3.2 Simulation of market scenarios

Figure 2 shows the N_2O emissions a farmer will choose on each acre of land when there is no GHG offset market (N_2O^*) and when the farmer can receive price P in an offset market for each unit of CO_2 equivalent GHG emissions that is reduced (N_2O_m). In general, farmers will choose emissions such that the marginal abatement cost is equal to the price they can receive for units of abatement. Thus, abatement increases with the price. Social welfare increases by the area W in Figure 2 because it is cheaper for sources with marginal cost equal to P to pay farmers to reduce emissions from their fields; total social abatement costs are lower. If the permit price is exogenous to farmers, then farmers' producer surplus will increase by area W.

We estimate baseline N_2O emissions, N_2O abatement, and the social benefit W from trading for an acre of each parcel in our study area. These calculations are simple for the linear model, but require calculation in Mathematica for the nonlinear model. We then aggregate these numbers to find total abatement and the benefit of trading for society. This process is repeated for three different scenarios. In all three cases we assume a market for tradable GHG permits exists, and the market price reflects the true industry marginal cost of abatement. Metcalf (2009) suggest that a U.S. carbon pricing policy of energy related carbon emissions due to either a tax or cap-and-trade system has a potential to raise carbon price to roughly \$15 per ton or \$0.0075 per pound;[5] we assume that price for our hypothetical market. In the first scenario we assume that farmers can receive the true market price of \$15 for an offset; this would be true if technology exists to permit perfect measurement of N_2O flows or if market rules were such that offset aggregators would be held harmless if actual N_2O flows did not end up being equal to the estimated amounts.

In the second and third scenarios we assume that imperfect emission measurement and legal structures cause agricultural offsets to receive a lower price than that which the market would naturally support. While farmers and point-source emitters may be profit maximizing, the regulators and policy makers who set the rules of the marketplace may choose to codify a penalty

[5] 1 short ton = 2000 lb.

on abatement accomplished by non-point sources if those policy makers are risk averse and concerned more with accomplishing abatement than with reducing damages from pollution (Horan, 2001). In scenario two, farmers receive a price that is 9% below market (Kurkalova, 2005) and in scenario three the price is 15% lower (Kim and McCarl, 2009).

Table 2. Results - N_2O Levels and Reductions Per Acre[a]

Offset Price[b] Scenario	Linear $N_2O(N)$			Nonlinear $N_2O(N)$		
	Baseline N_2O[c]	N_2O Reduction[c]	Social Surplus from Trading (W)	Baseline N_2O[c]	N_2O Reduction[c]	Social Surplus from Trading (W)
$.00750/lb	0.789 (0.778)	0.042 (0)	$0.16 (0)	1.87 (0.109)	0.333 (0.035)	$1.37 ($0.15)
$.00682/lb	0.789 (0.778)	0.038 (0)	$0.13 (0)	1.87 (0.109)	0.310 (0.033)	$1.15 ($0.13)
$.00637/lb	0.789 (0.778)	0.035 (0)	$0.11 (0)	1.87 (0.109)	0.294 (0.032)	$1.01 ($0.11)

[a] Each cell gives the mean with standard deviations in parentheses, calculated over a representative acre for each of 1,361 individual parcels.
[b] GHG offset prices are dollars per pound of CO_2 equivalent GHG emissions per year.
[c] Emissions and reductions are expressed in 1,000 lbs of CO_2 equivalent emissions per year and assume the parcels are all in the corn phase of a corn/soy rotation.

Table 3. Results - Aggregate N_2O Changes and Welfare Improvements[a]

Offset Price[a] Scenario	Linear $N_2O(N)$			Nonlinear $N_2O(N)$		
	N_2O lbs. reduction[b]	N_2O %[c] reduction[b]	Social Surplus from Trading (W)[d]	N_2O lbs. reduction[b]	N_2O %[c] reduction[b]	Social Surplus from Trading (W)[d]
$.00750/lb	3,349	5.3%	$12,557 ($15.62)	26,925	18%	$110,634 ($137.66)
$.00682/lb	3,045	4.8%	$10,383 ($12.92)	25,040	17%	$92,961 ($115.67)
$.00637/lb	2,844	4.5%	$9,059 ($11.27)	23,748	16%	$81,983 ($102.01)

[a] GHG gas offset prices are dollars per pound of CO_2 equivalent GHG emissions per year.
[b] Emissions and reductions are expressed in 1,000 lbs of CO_2 equivalent emissions per year and assume the parcels are all in the corn phase of a corn/soy rotation.
[c] The baseline aggregate N_2O emissions are 63,589 1,000lb/yr for the linear case and 150,574 for the nonlinear case.
[d] Total social surplus from trading (W) is given, with value per 100 acres in the study in parentheses. The latter equals total social welfare divided by total acres in the study area (80,368) multiplied by 100.

Tables 2 and 3 give the results of the simulated price scenarios. We focus first on the results that obtain when N_2O emissions are a linear function of fertilizer application rates. Average N_2O reductions per acre would be only.035 pounds in the scenario with the lowest price; there is no variation in per-acre reduction because the slopes of all the marginal abatement cost curves for N_2O reductions are the same. Those reductions add up to 2,844 thousand pounds in the entire study area. Eliminating the price discount entirely would bring those numbers up to .042 pounds per acres and 3,349 thousand pounds overall, an 18% increase. These are not large proportionate reductions in emissions, only ranging from 4.5% with the lowest price to 5.3% with the highest price.

When N_2O emissions are a linear function of N rates, the benefit to society of the best no-discount price scenario is \$0.16/acre (\$12,557 over the study area), which is \$0.05 (\$3,498 overall) higher than what we would gain if uncertainty caused a 15% price discount. Thus, if technology prevents a 15% discount, society gains \$4.35 for every 100 acres. If the absence of good monitoring technology meant the market would not exist at all, we can think of the benefit of such technology as being \$15.62 per 100 acres.

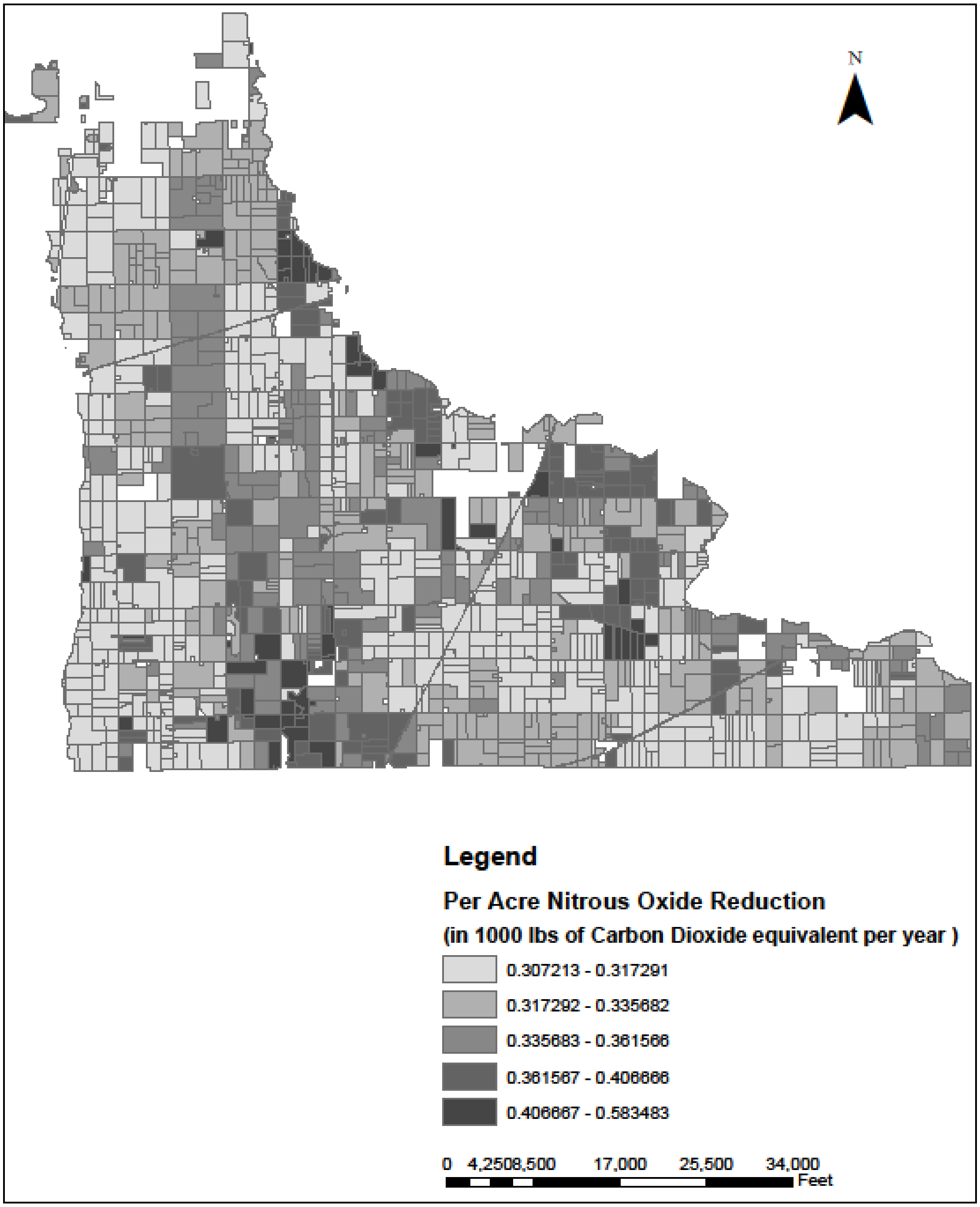
The results are very different when N_2O emissions are an exponential function of fertilizer application rates. Average baseline N_2O emission rates are 1.87 pounds per acre, up from .789 pounds per acre in the linear results. Because profit maximizing baseline fertilizer application rates vary across parcels with their average soil quality, the marginal abatement cost curves for N_2O reductions have heterogeneous shapes. As a result, a given offset price induces heterogeneous N_2O reductions per acres across parcels and yields varied per-acre increases in social welfare, as shown in Figures 3 and 4. Average N_2O reductions range across scenarios from .333 (with no price discount) to .294 (with the biggest price discount) pounds per acre; those reductions are larger in absolute value and as a percentage of baseline emissions than the per acre reductions of the linear model.

The benefits to society of offset trading are almost an order of magnitude higher in the scenarios with nonlinear N_2O emission production. The increase in social surplus from offset trading ranges from \$1.01/acre with the lowest price (\$81,983 over the study area) to \$1.37/acre with the highest price (\$110,634 overall). Technology that eliminated a 15% price discount would have a social value of about \$36 per 100 acres. If uncertainty prevented trading entirely, technology that allowed full-price offset trading would be worth about \$137 per 100 acres.

4. Conclusions

Early studies of N_2O emissions from row-crop agriculture modeled N_2O emissions as a linear function of fertilizer application rates. If that model holds true, our results imply that N_2O emission offset sales have limited potential in corn/soybean fields such as those found in Central Illinois. In our study area, even a perfect market induced farmers only to reduce N_2O emissions by around 5%. The benefits of technology that would increase the accuracy of N_2O emission monitoring (and thus eliminate any price discount associated with uncertainty about agricultural emissions) would be at most \$15 for a 100-acre field – probably too small to justify the technology.

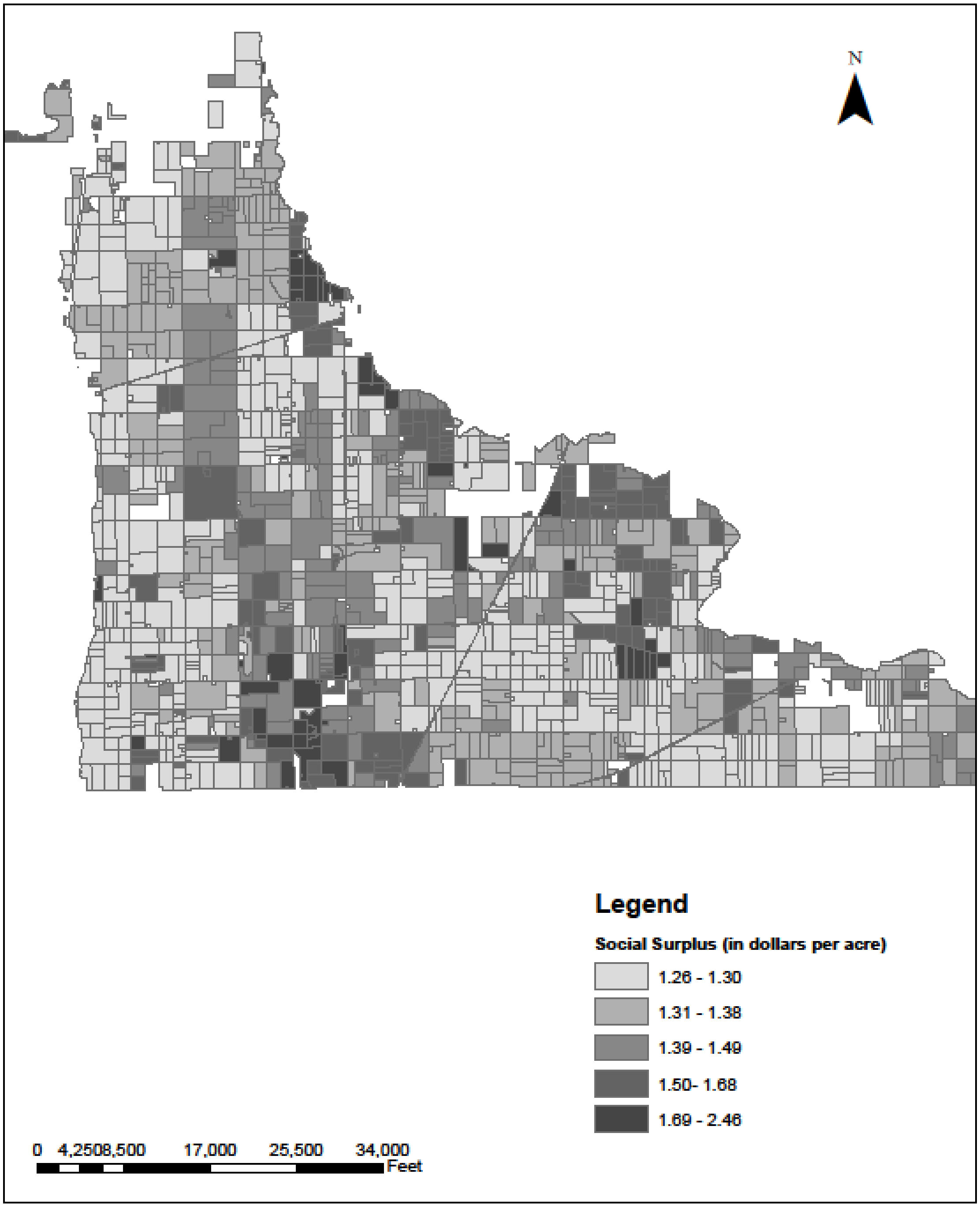
Figure 3. Per Acre N_2O Reductions, by Parcel[a]



*Created by using Tiger shapefiles downloaded from http://www.census.gov/geo/www/tiger/ Sept 2011.

[a] Results are for no price-discount scenario and N_2O a nonlinear function of N.

Figure 4. Per Acre Social Surplus from Trading, by Parcel[a]



*Created by using Tiger shapefiles downloaded from http://www.census.gov/geo/www/tiger/ Sept 2011.

[a] Results are for no price-discount scenario and N_2O a nonlinear function of N.

However, recent work (McSwiney and Robertson, 2005; Millar *et al*., 2010) emphasizes the nonlinear nature of N_2O emission generation as a function of fertilizer application rates. If this model holds true, then a perfectly functioning market for N_2O offset credits could induce farmers to reduce N_2O emissions by as much as 18%. The benefit of technology that helps this market to exist could range as high as $138 for a 100-acre field. Improvements in sensor technology might well bring the cost of this kind of infrastructure down to where its benefits justify its costs.

The profit per acre to be gained from a well-functioning market varies across space with a standard deviation that is 11% of the mean (as shown in Figure 4). Some farmers will surely find it in their own best interests to install such technology, though others may not. As long as policy allows trades when monitoring technology is installed only on the fields that are involved in trades, socially efficient technology installation will occur across the landscape.

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