Journal of Agricultural and Resource Economics 36(3):552–572

The Role of Information and Prices in the Nitrogen Fertilizer Management Decision: New Evidence from the Agricultural Resource Management Survey

James M. Williamson

This article investigates the impact of agronomic and price information on nitrogen fertilizer management. Excessive nitrogen applications can cause environmental degradation, and it is important to understand how information influences the application decision in order to develop effective conservation policies. The impact of soil N-tests on the rate of applied nitrogen is estimated. Farmers who use a soil test reduce their use of commercial nitrogen by up to 83 lbs/acre relative to non-testers. New evidence indicates that rising fertilizer prices encourage farmers to manage nitrogen more carefully. Estimated price elasticities of quantity demanded range from -1.67 to -1.87.

Key words: nitrogen demand elasticities, nitrogen fertilizer management, nonpoint source pollution, soil N-testing

Introduction

Much of the nitrogen used in agriculture is unnecessary from an agronomic standpoint, but farmers may apply chemical nutrients in levels that exceed agronomic targets for many reasons, including risk management and the relatively low costs (Yadav, Peterson, and Easter, 1997; Sheriff, 2005; Trachtenberg and Ogg, 1994). Over-application deposits more nitrogen on the field than the crop can use, and the surplus is susceptible to loss through surface flow, leaching (soluble nitrate), and volatilization (particularly urea and ammonia).

Excess nitrogen in the environment can exact costs on society.[1] High levels of nitrate and its by-products in municipal water supplies require treatment, and contaminated domestic wells pose a human health risk–particularly to young children–through the biological conversion of nitrate to nitrite (U.S. Environmental Protection Agency, 2006). Excessive nitrogen loads in the environment also contribute to eutrophication of waterway, limiting commercial and recreational opportunities. In the Gulf of Mexico and other bodies of water downstream of intensive agricultural practices, nutrient-rich waters encourage the growth of algae blooms, which consume oxygen and result in large hypoxic zones (Rabalais, Turner, and Wiseman, 2001). These nutrients are also a suspected cause of outbreaks of *Pfiesteria piscicida* or *Pfiesteria*-like dinoflagellates, which have been linked to fish kills (Burkholder and Glasgow, 1997). A recent analysis estimates the value of recreational water use, property value, wildlife, and drinking water lost at over $2.2 billion annually (Dodds et al., 2009).

James M. Williamson is an economist with the Economic Research Service, USDA. The views and opinions expressed in this article do not necessarily reflect those of the United States Department of Agriculture.
The author thanks Chris Dickens and Ryan Williams for assistance with GIS data preparation, and Mike Livingston for ARMS data assistance. Marc Ribaudo and three anonymous referees provided valuable comments.
Review coordinated by Myles Watts.

[1] Samples indicate that background levels of nitrogen are approximately 1 mg/L in relatively undeveloped areas not impacted by agricultural production (U.S. Geological Survey).

Despite the known harm, high nitrogen nutrient loads continue to flow into the environment. In 2008, over 350,000 metric tons of nitrogen, dissolved nitrite and nitrate, was delivered to the Gulf of Mexico. The flux contributed to over 20,000 square kilometers of bottom-water hypoxia. Over time, the nitrogen load in the Gulf of Mexico has varied considerably. In 2000, less than 150,000 metric tons of flux was delivered (U.S. Geological Survey, 2009). Spikes in nitrogen loadings (over 350,000 tons of nitrogen) have been observed in 1979, 1983, 1984, and 1999.

The first goal of this article is to investigate the value of nutrient management information farmers receive from several common sources. Understanding how information influences nutrient application decisions on the field is important for developing strategies for nitrogen load mitigation. It is commonly held that management practices can reduce the movement of agricultural chemicals from the field to surface and groundwater. A prime example is the soil N-test. Soil N-test recommendations can reduce uncertainty about soil nitrogen available to plants; this information may encourage farmers to apply nitrogen at a rate compatible with the crop's assimilative capacity. The second goal of this article is to document the changing role of nitrogen fertilizer prices in application rate decisions. The recent rise in the price of nitrogen fertilizer has implications for nitrogen use efficiency (NUE).[2]

This paper makes several important innovations to the literature concerning the quantity of nitrogen demanded and its management. Using field-level microdata from the USDA's Agricultural Resource Management Survey (ARMS), I estimate nitrogen application rates using an instrumental variables (IV) approach to overcome identification issues presented by farmer heterogeneity and endogenous soil N-testing. Notably, this is the first research to instrument for nitrogen price using a cross-section of data by exploiting exogenous spatial variation between domestic ammonia production plants and corn field locations.

My results have strong policy implications. Despite decades of relatively price-insensitive nitrogen demand, results suggest that farmers are becoming more sensitive to nitrogen fertilizer prices. Further, while prices are important to the quantity of nitrogen demanded, they also play a role in other management behavior of famers. The results also show that soil N-testing can be an effective management practice for reducing nitrogen loss.

Nitrogen Prices: Consequences for Management Decisions

Historically, research on nitrogen demand suggests that responses can vary widely, depending on the source and time period the data cover, the type of econometric methods used, the type of crop to which the nitrogen fertilizer is applied, or whether the study covers a single crop or is sector-wide. While no true consensus exits, the bulk of research has reported relatively price-inelastic demand for nitrogen fertilizer. Burrell (1989) provides a convenient summary of fourteen empirical demand studies through the 1980s. Of those fourteen studies, only four report elasticities greater than unity, with estimates ranging from -0.20 to -0.70 (see Griliches, 1958; Heady and Yeh, 1959; Carman, 1979; Ray, 1982; Shumway, 1983).

More recent contributions include Denbaly and Vroomen (1993), who use cointegrated and error-corrected models with U.S. time series data from 1964 to 1989 to estimate corn producers' short and long-run Marshallian nitrogen demand elasticities. They report a short-run Marshallian elasticity of -0.21 and a long-run elasticity of -0.41. Hansen (2004) estimates Danish farmers' quantity demanded of nitrogen using an unbalanced panel spanning 1982 to 1991. The study covers all crop types and concludes that nitrogen quantity demanded is insensitive to own-price, with an elasticity of -0.45.

Not all studies have found the price elasticity of demand for nitrogen fertilizer to be inelastic. Notably, Heady and Yeh (1959) report national and regional estimates of quantity demanded using

[2] NUE is defined as the proportion of all nitrogen inputs that are removed in the harvested crop (Cassman, Dobermann, and Walters, 2002).

Table 1. Reported Changes in Commercial Nitrogen Fertilizer Management

	2001	2005
Reduced Nitrogen	0.11	0.24[b]
	(0.011)	(0.02)
How much[a]	0.21	0.17[b]
	(0.02)	(0.83)
Increased manure	0.02	0.03[b]
	(0.01)	(0.06)
Changed the type of N	0.02	0.05[b]
	(0.01)	(0.01)
Managed N more carefully	0.08	0.21[b]
	(0.01)	(0.02)
Observations	1,646	1,377

Notes: Data are weighted. Jackknife standard errors in parentheses. Data are from the Agricultural Resource Management Survey, years 2001 and 2005.
[a] Only reported if reduced N.
[b] Statistically different from 2001 values at the 1% level of significance.

a time-series of data from 1910 to 1956 and find the national estimate to be -1.71, though this figure includes nitrogen, potassium, and potash together. Roberts and Heady (1982) also use annual time-series data from the United States, but spanning 1952 to 1976, and find price elastic demand for nitrogen applied to corn (-1.15). Carman (1979) examines the nitrogen demand in eleven western states and finds significant state-level variation in elasticities. Statistically significant elasticity estimates in Carman's study range from -0.55 to -1.84 and demonstrate that elasticity of quantity demanded can vary significantly, even within a production region. In a study of fertilizer in general, Weaver (1983) investigates the demand in just two states, North Dakota and South Dakota, and finds fertilizer demand to be elastic, ranging from -1.38 to -2.16.

In 2001, the ARMS incorporated a unique set of questions designed to solicit farmers' attitudes toward a recent change–some might say a spike–in the price of commercial nitrogen. The questions asked whether farmers reduced their application rates of commercial nitrogen as a result to the higher prices, and if so, by how much. In addition, farmers were asked whether they increased the use of manure or other organic nitrogen, whether they switched to a different form of commercial nitrogen, and whether they managed the nitrogen on the field more carefully.

Table 1 presents a summary of the self-reported effects of higher nitrogen fertilizer prices on the application of nitrogen. For production year 2001, about 11% of farmers said high nitrogen fertilizer prices were a reason they reduced the amount of fertilizer applied to the field. Of those who reduced applied amounts, the average reduction was 21%. Changing the way nitrogen is managed is another method farmers used to reduce the amount of nitrogen applied, primarily by changing the timing or method of application. In 2001, 8% of farmers reported managing their nitrogen more carefully. Few reported they changed the type of nitrogen or substituted manure for commercial nitrogen fertilizer. In 2005, a greater share of farmers responded that high nitrogen fertilizer prices caused them to reduce the amount applied (24%), and those who did reduced by 17%. The biggest difference came in the way fertilizer was managed. Nearly three times as many farmers reported that they managed their nitrogen fertilizer more carefully. A relatively small number of farmers reported changing the type of nitrogen used, but that number more than doubled compared to 2001. Finally, a relatively small fraction of farmers reported an increased use of manure resulting from higher commercial nitrogen prices.

Changes in farmer responses over time present an interesting case for policy design, and comparing response data with recent price data can provide perspective on price and reported

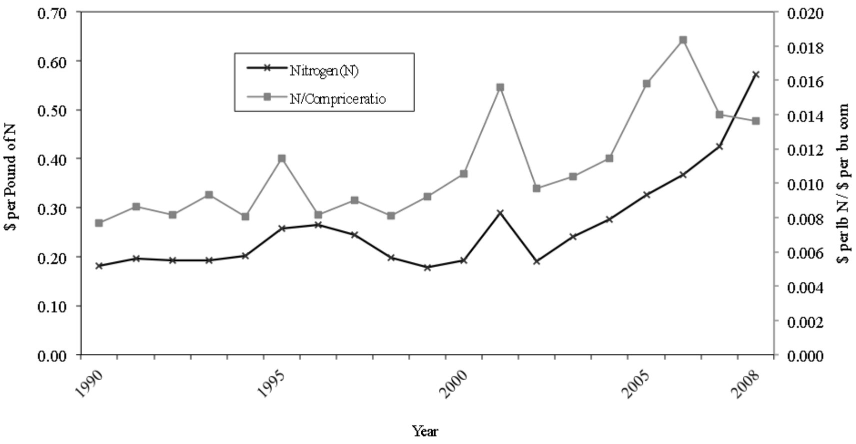

Figure 1. U.S. April Nominal Prices of Fertilizer Nutrients

Notes: Data are from the Economic Research Service, using data from USDA, National Agricultural Statistical Service.

changes in management behavior. Historical data presented below in figure 1 reveal several features of recent nitrogen prices. First, and arguably most importantly, the recent past market for nitrogen can be characterized by rapid price acceleration. From 1999 to 2008, the price of nitrogen quadrupled. In the mid- to late-1990s this was not the case; before 1999, nitrogen prices had been falling. Prior to 1999, the most recent price peak was in 1996, when the price of nitrogen reached 26 cents/lb.; after the peak, the price fell to 18 cents/lb. In 2001 there was a major jump in the price in nitrogen and prices rose 50% from 2000 levels. After the average price settled back to pre-2000 levels in 2002, the price began to rise again–this time by more than 10% yearly–and continued to climb through 2008.

Because the price of the crop plays a role in the quantity of nitrogen demanded, the changing price of fertilizer inputs can be analyzed in relation to the price of the crop, in this case corn. Figure 1 reveals that the nitrogen fertilizer price growth has outpaced the growth of corn prices; that is, the line representing the price ratio of nitrogen fertilizer to corn is increasing over time. If corn prices had kept pace with nitrogen prices, farmers would have been reluctant to reduce their input use and forego profits from higher corn prices; however, corn prices did not increase as dramatically.[3]

Generally, it is assumed that expectations about future prices are formed, in part, by recent prices. Self-reported behavior supports the hypothesis that farmers' expectations play a large role in their behavior.[4] The differences in farmers' self-reported prices effects between 2001 and 2005 surveys provide some evidence of this behavior. Following a period of price drops, a sudden jump in the price did not induce a large reported change in behavior; a relatively small number of farmers reportedly reduced their application rate. The data for 2005, however, tell a different story. Steady price growth prompted more farmers to reduce their nutrient use, despite the fact that the change from 2004 to 2005 was smaller than the change from 2000 to 2001. In fact, the price change from 2004 to 2005 was only 18%, compared to 50% in 2000-2001, and the price of commercial nitrogen in 2005 was only 4 cents higher than the 2001 price. Still, the number of farmers who reported that the price of nitrogen caused them to reduce the amount applied was more than double that of 2001.

Clearly, prices matter for applied amounts (quantity demanded), but prices also influence management behavior on the farm, and farmers' answers to questions about high prices have policy

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[3] Between the 2001-2002 and 2006-2007 marketing years, the price per bushel of corn rose 54% (U.S. Department of Agriculture, National Agricultural Statistics Service, 2009).

[4] See Muth (1961) for a discussion of prices and expectation and Chow (1989) for an analysis of adaptive expectation's performance.

implications. Again, reported management changes were far more prevalent in 2005 than 2001. In 2005, 21% of the farmers in the survey reported that they managed their nitrogen more carefully. Further, substitution of manure for nitrogen in response to higher prices was also more pronounced in 2005 than 2001, though the use of manure was still small in both years. Self-reports by farmers are instructive and provide evidence that farmers are managing nutrients differently in response to changing prices and expectations.

Identification Strategy

Research using observational data presents econometric challenges; this is particularly true of research examining the effect of potentially endogenous variables on a study population. In this case, when estimating the effect of N-soil tests on application rate, it is unclear why two observationally identical farmers make different choices about testing the soil. The underlying problem in the relationship is that unobserved heterogeneity is responsible for determining whether a farmer conducts a test; a farmer who tests the soil regularly may also have unobserved preferences for land stewardship. If differences beyond observed field, farm operation, and operator characteristics play a role in determining who conducts the test and how the test is used, then the test may be endogenous to the amount of N applied.

Nitrogen price also presents a challenge in a sample of microdata. Nutrient costs were reported in the USDA's ARMS data as total fertilizer cost per acre, but never by the chemical component, (e.g., neither the total cost of nitrogen nor its per-acre cost were reported). Therefore, I broke out the per acre cost of N from the total per acre cost of fertilizer, which consisted of N, P, and K, by multiplying the relative amount of N fertilizer applied to the field by the total cost per acre of fertilizer to derive a per acre cost. I scaled the price using the ratio of the national average price for N to the national average combined price for NPK.

$$
\begin{aligned}
(1) \qquad NPrice = &\text{ N's \% of total fertilizer applied} \\
&\times \text{ ratio of N's price relative to national mean fertilizer price} \\
&\times \text{ total fertilizer cost per acre}
\end{aligned}
$$

Whenever prices are constructed as a share variable they are likely to embody an error-in-variables, because the relative amount of N applied may not be the same as the relative price of N to the total price of fertilizer–in other words, the ratio does not reflect the true price. To see how this effects the estimation of quantity demanded consider the observed price of nitrogen is a function of the true, unobserved price plus a disturbance term, v.

$$
(2) \qquad P^{Observed} = P^{True} + v.
$$

Because $P^{Observed}$ is a function of P^{True} and v, an ordinary least squares (OLS) model estimate of quantity demanded using $P^{Observed}$ will be biased and inconsistent. Specifically, in the classic errors-in-variables example, the coefficient in an OLS model will be biased toward zero.[5]

There are two issues that should cause concern with the price construction. First, the prices farmers pay for fertilizer may change with their level of quantity demanded, and the error term v could embody unobserved quantity discounts farmers receive. If this is true, their application rate is correlated with total quantity demanded, and failing to account for this also results in bias. Second, if the relative amount of N applied is correlated with total fertilizer amount, then this too could cause bias. To test for such a relationship in the latter case, I regress the relative amount of nitrogen on the total quantity of fertilizer applied. This tells us whether, *ceteris paribus*, increased fertilizer use increases the relative amount of nitrogen, and therefore the denominator in the price calculation.

[5] See Greene (2000) for a formal discussion of measurement error and the resulting attenuation bias.

In this case, I cannot reject the null of no relationship between the relative amount of N and total quantity, even at the 10% level. However, testing the former case is not feasible from the available data, because the N price variable is a function of the relative amount of N and total price per acre, which includes N, P, and K.

To overcome the problem of mismeasured nitrogen prices and endogenous soil testing I employ an IV approach. In the case of endogenous N-soil testing, average annual precipitation is an instrument that is correlated with N-soil testing but uncorrelated with the disturbance process. Because higher average annual precipitation generally reduces the ability to conduct soil tests, I therefore expect annual average precipitation to be negatively related to N-soil test.[6]

I identify the nitrogen own-price effect on quantity demanded using three sources of exogenous variation: distance between the field and domestic ammonia fertilizer production; production capacity of nearby ammonia plants; and distance from the field to New Orleans, LA, site of the majority of international ammonia importation. These variables are useful instruments because the distance between the field and production capacity are arguably uncorrelated with the behavior of the farmer or the placement of the field;[7] therefore, the instruments capture the exogenous variation in price and use it to estimate application rates. Figure 2 shows the relationship between domestic ammonia production and a sample of corn fields for years 2001 and 2005 (International Fertilizer Development Center). Distances from the field to ammonia production are calculated using the location of the plant and geo-coded field samples from the ARMS.[8] I hypothesize that variation in the distance from the field to production capacity and importation leads to differential transportation costs and local market conditions that drive price variation throughout the country. In addition to domestic production, ammonia is increasingly being imported into the United States. A majority of the ammonia enters the United States from the Gulf of Mexico, and, specifically, New Orleans, Louisiana (Huang, 2007). I therefore also include an instrument that specifies distance to New Orleans.

Figure 2 illustrates that corn production in the sample is clustered in the Corn Belt, the upper-Midwest, and the Northern Central Plains, while ammonia production capacity is clustered in the South, particularly the South Central region. The size of the points representing the location of production varies proportionally with production capacity. Additionally, some cities have more than one plant. Although a quarter of production facilities in 2001 were located throughout the Corn Belt, 50% of the domestic nitrogen fertilizer production capacity was concentrated near the source of the primary input, natural gas, in the American South and South Central regions. Furthermore, the South Central region produced 44% of domestic capacity.

On average, a field was 322 kilometers (201 miles) away from the closest ammonia plant and 1,295 kilometers (809 miles) from New, Orleans. The average total domestic capacity during 2001 and 2005 was 17,412 tons, and the average capacity of the nearest production plant was 364 tons.

[6] Questions have been raised about the validity of the precipitation measure instrument. Some have noted that the instrument is problematic if the prospect of a rainy spring affects the rate of application. A rainy spring could increase the probability of loss and cause the farmer to hold back application or re-dress a lost application. Precipitation could also influence the rate though soil moisture content, which is in part related to rainfall, but is also influenced by soil texture and other field properties, such as tile drainage. Since the weather at the time of planting is unknown, I use control variables to account for precipitation and other factors that affect soil moisture, namely tile drainage and soil percolation rate. In particular, the soil percolation rate–which is a function of precipitation rate–will capture much of the effect precipitation has on the concerns the reviewer has pointed out. While I hypothesize that higher levels of average annual precipitation reduce the probability of testing the soil, there is a chance the disturbance process is not completely free of the effect of rain's influence at the time of planting and plant emergence. I test the exclusion restrictions and cannot reject the hypothesis that the set of excluded instruments (including the excluded instruments identifying N price) are not jointly correlated with the disturbance process.

[7] To test that the instruments are uncorrelated with the residual component in the second stage of the IV model, or exogenous to the rate of fertilizer application, I test overidentification restrictions using a Sargan test. The test statistic is computed as nR^2 and has a $chi^2(k - r)$ distribution, where k is the number of instruments and r is the number of endogenous variables. The results of the test are presented later.

[8] It should be noted that these are sample points, not representative of all corn production in the United States; however, when I estimate a model of nitrogen demand, the sample points are weighted to reflect total U.S. corn production.

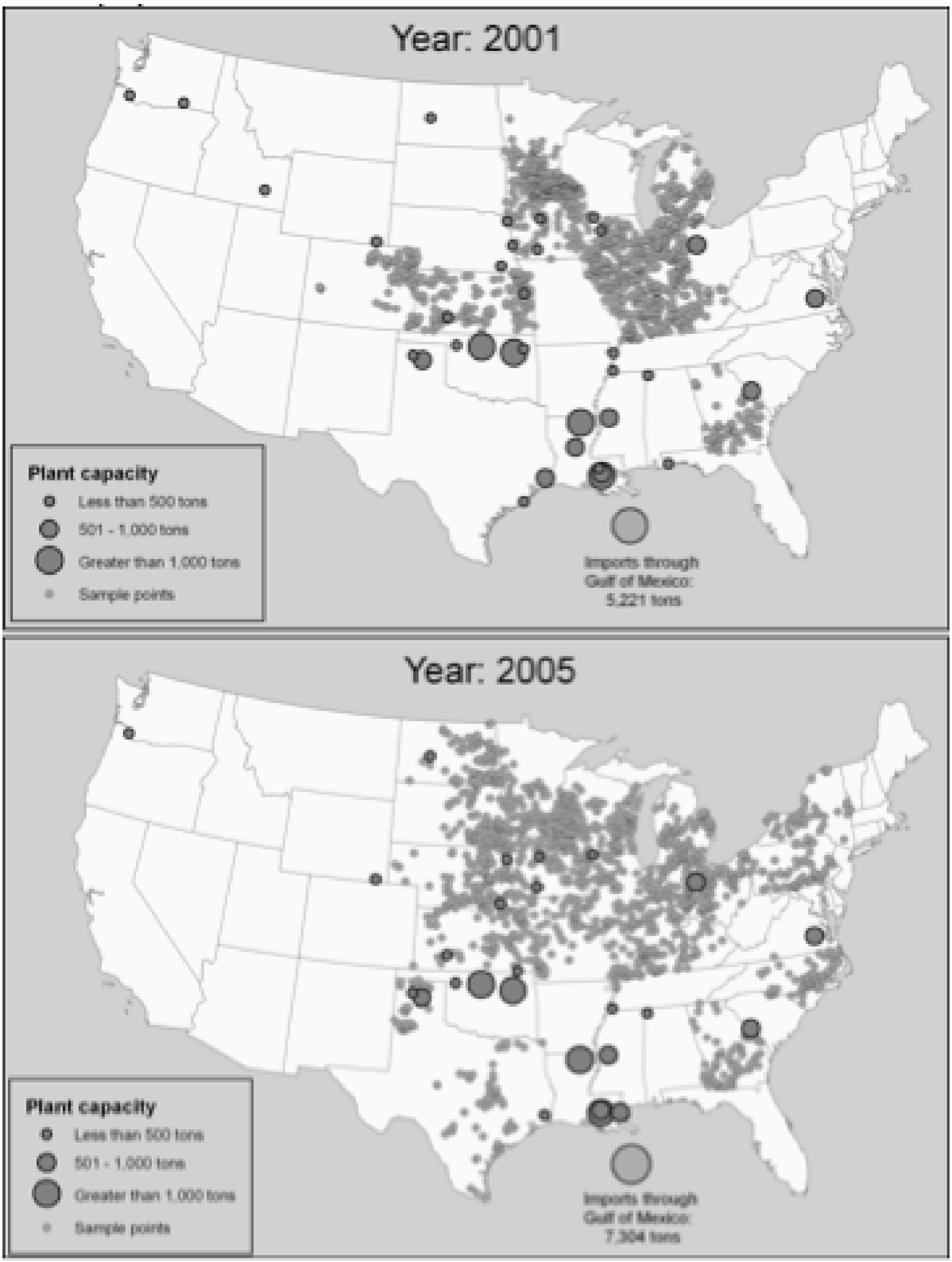

Figure 2. Domestic Ammonia Production Capacity, Ammonia Imports, and ARMS Corn Field Sample Points

Notes: Each sample point represents a single corn field. To protect against disclosure, the sample points are offset with a small degree of error from their true location on the map. Data are from the International Fertilizer Development Center and the United States Department of Agriculture, Agricultural Resource Management Survey, years 2001 and 2005.

Table 2. Description of Excluded Instruments (N = 2,874)

Instrument Name	Description	Mean	95% Confidence Interval	
Nola_dist	Distance to New Orleans, LA (meters)	1,295,467	1,269,047	1,321,887
Near_dist	Distance to nearest ammonia plant (meters)	322,071	308,713	335,430
Plant_cap	Capacity of closest ammonia plant (short tons)	364.15	355.49	372.81
Cap3	Total capacity of closest three ammonia plants (short tons)	1,076.92	1,058.96	1,094.89
Avgprecip	Average precipitation (annual inches)	34.15	33.78	34.52

Notes: Data are from the International Fertilizer Development Center; National Commodity Crop Productivity Index (USDA).

Further, there were 40 active ammonia plants in 2001, but that number dropped to 30 plants by 2005 due to closures and idling. Table 2 summarizes distance and capacity data, along with the other instruments used to identify N-soil testing probability. Figure 3 presents evidence of regional price variation through a time series of nominal ammonia prices by region for 1990-2005.[9] Ammonia prices have traditionally been lowest in the South Central region, which has an outsized share of ammonia production.[10] Although prices across all regions generally display the same trend, farmers in the Northwest consistently face the highest nitrogen fertilizer prices, which is not surprising given that the region housed only one production plant in 2005 and is furthest from the Gulf of Mexico. During 1999-2005, prices in the Northwest were 36.4% to 100% higher than prices in the South Central region. In fact, even in the East South Central region, ammonia prices were 4.1% to 28.4% higher than the South Central region. Arguably, the differences illustrated in figure 3 are driven by variations in the distance to ammonia production and capacity of the plants.[11]

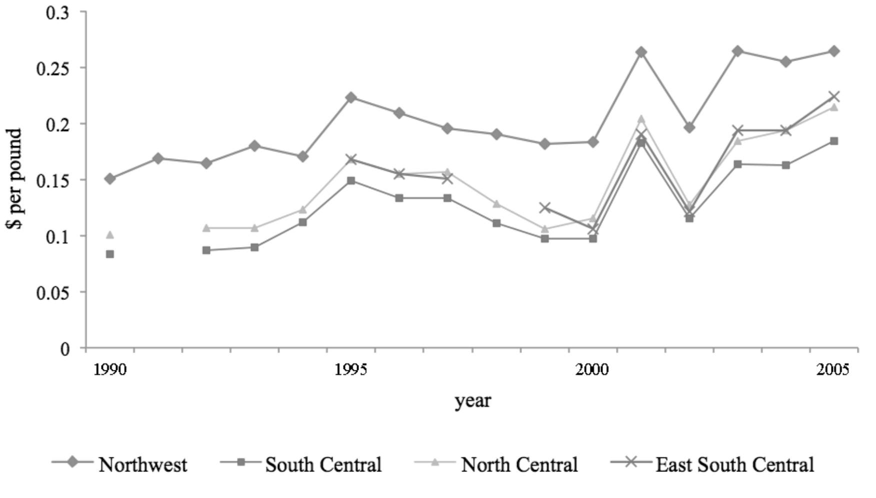

Figure 3. Regional Nominal Ammonia Prices (April)

Notes: Data are from the USDA, National Agricultural Statistics Service.

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[9] Data were not available for all regions in all years.

[10] States in the region with ammonia production are Louisiana, Mississippi, Oklahoma, and Texas.

[11] It should be noted that prices may also differ by the form of nitrogen used. Although I cannot distinguish the form of nitrogen, I can control for some methods of application which correspond with certain forms, for example injection versus broadcast. The timing of application can also tell us something about the form of nitrogen applied (a fall application is more likely to be fertilizer in the form of anhydrous ammonia).

Model

I use a two-stage model specified with two endogenous variables to estimate a partial-equilibrium static demand model derived from profit maximization theory. The model assumes producers make immediate adjustments to quantity demanded in response to changes in price, and that prices are known at the time of production planning. These assumptions are reasonable given the ability of farmers to enter into contracts that establish price for delivered corn and inputs to production, such as forward or marketing contracts, and other hedging instruments. Further, production technology is assumed known and fixed. Since only two time periods separated by four years are used, technology is unlikely to change. The most likely technological change is that of seed technology–the use of genetically modified (GMO) corn; however, the model specification controls for this. If GM corn seed returns a greater yield than non-GMO (that is, GMO technology increases the marginal productivity of the corn seed), then the rate of nitrogen fertilizer application should decrease, *ceteris paribus*. In 2001, 20% of corn acres were planted with GMO corn; in 2005, the amount was slightly greater than 30%.

I characterize the problem posed to the farmer as one of profit maximization with uncertainty, as evidenced by the nitrogen overtreatment, but the decision of the farmer could also be conceptualized as a utility maximization problem. In this case, the farmer chooses a level of output that maximizes the farmer's initial wealth plus expected profit from the operation. Under utility maximization a farmer considers not only expected profit but moments of the profit distribution as well, and deviations from the recommended level of nitrogen then depend on the farmer's level of risk aversion. Evidence from field trials suggests that risk-neutral farmers would be willing to over-apply nitrogen in order to increase profits during a year of "good" growing conditions (Rajsic, Weersink, and Gandorfer, 2009). On the other hand, risk-averse farmers will attempt to minimize profit variance; this could be through an over- or under-application of nitrogen, depending on the source of risk. In practice, my empirical results are not dependent on the conceptual framework; in both cases, nitrogen prices enter the profit function and the identification strategy would not change. Rather, the level of risk aversion primarily drives the differences. Some research, however, suggests that risk-averse farmers are more responsive to price because of profit risk (Just, 1975; Roosen and Hennessy, 2003; Rajsic, Weersink, and Gandorfer, 2009). If farmers are on average risk-averse, my elasticity estimates will represent an upper bound.

The following system of equations estimates quantity demanded:

$$Y_{irt} = \alpha_1 + \hat{T}_{irt}\beta_1 + \hat{P}_{irt}\lambda_1 + \boldsymbol{X}_{irt}\delta_1 + \phi_{1r} + \upsilon_{1t} + \varepsilon_{irt}, \tag{3}$$

$$T_{irt} = \alpha_2 + \boldsymbol{X}_{irt}\beta_2 + Z^T\delta_2 + \phi_{2r} + \upsilon_{2t} + \kappa_{irt}, \tag{4}$$

$$P_{irt} = \alpha_3 + \boldsymbol{X}_{irt}\beta_3 + Z^T\delta_3 + \phi_{3r} + \upsilon_{3t} + u_{irt}. \tag{5}$$

Equation (3) is the outcome equation, where Y represents the log transformed per-acre rate of nitrogen applied to the field of farm i in USDA production region r at time t. Endogenous variables, $\hat{T}$ and $\hat{P}$, are estimated N-soil testing probability and nitrogen price from equations (4) and (5). The set of excluded instruments for N-soil test are represented by Z^T, and the excluded instruments used to estimate nitrogen price are represented by Z^P. The vector $\boldsymbol{X}$ is a set of independent variables that includes characteristics of the operator, farm operation, and the field; the disturbance term is represented by ε.

A case can be made that country-wide trends affect nitrogen use over time. Perhaps in response to outreach efforts to reduce fertilizer runoff due to over-use, for example, environmental awareness campaigns that communicate the benefits of reduced nitrogen in the environmental, attitudes about nitrogen rates have changed. I control for trends in nitrogen use that change over time with a time effect term, υ_t. Nitrogen use across production USDA-defined regions may also affect application rates, therefore I control for region specific factors with a fixed effect term, ϕ_r.

Data

The data are cross-sectional and come from the U.S. Department of Agriculture's Agricultural Resource Management Survey (ARMS), which is a series of interviews with farm operators designed to solicit information about production practices, costs of production, business finances, and operator and household characteristics. Commodity-specific surveys are fielded on a rotating basis, usually every 5 to 8 years. I focus on corn production because of its intense nitrogen use, for which the ARMS last fielded surveys in 2001 and 2005.

I use data from two components of the ARMS. The first component surveys the farm enterprise's costs of production and a host of production practices at the field level (ARMS date). The second component collects in-depth financial information concerning the farm business and the household of the operator (ARMS date). The two components can be linked to provide a complete view of the farm operation from the farm's representative field to its financial statement, and I restrict my sample to farmers who completed both surveys.

I include farmer characteristics as covariates, including age, education, whether the farmer earned income from work off the farm, and net farm income, which in some cases could be negative. Age and education are common proxies for managerial ability. Income earned from work off the farm is used as a measure of the reliance on farm income. Net farm income includes, among other things, earnings from crop production, rents, government payments, and patronage dividends. The price received for corn is also included. The implicit price received for a harvest was calculated by dividing the net value of the product (harvest) by the total number of bushels of corn produced and not used on the farm. The net value of product was calculated by multiplying a state composite price by net bushels produced. The state composite price is an average calendar year price and represents the average "farm gate" price. The composite price embodies expectations to the extent that farmers enter into marketing and other forward contracts.

I account for land quality and tenancy issues by including the per-acre annual value of production, the per-acre value of the land, and acres owned by the operator. I also control for environmental characteristics of the field, such as whether any part of the field is classified as a wetland. The presence of livestock and a nutrient management plan on the farm may indicate a greater reliance on manure, often driven by the need to dispose of manure. I account for these with dummy variables as well. The nutrient requirements of a current corn crop are also based, in part, on the plant-available nutrients existing in the soil; past cropping practice can influence these nutrients. Therefore, I use a dummy variable to control for crop rotation pattern of three-year straight corn rotation.

The timing and method of application may also be important determinants of application rate. A spring application is better timed to meet the plants' needs for nutrients and reduces the risk of loss due to environmental factors relative to a fall or winter application. On the other hand, farmers may opt to apply nitrogen in the fall, when there are fewer time demands and prices are often lower. In such a case, a nitrogen inhibitor is often used to further slow the nitrification process, though average annual nitrate losses can still be 50% higher under fall application compared to spring application (Randall and Mulla, 2001). To counter this, in many cases anhydrous ammonia is injected into the soil because low temperatures at this time of the year slow down the conversion of ammonia to ammonium and nitrate, reducing the loss of nitrogen. I control for the method of application with a dummy variable indicating whether the nutrient was incorporated or injected into the soil and for time of year, with a dummy variable for spring application.

Technology and other management practices thought to affect nitrogen rate are captured by explanatory variables indicating the use of field irrigation and GMO corn seed. Irrigation is an important component in nitrogen management and may be a necessary practice because of climate, or it may be a way of controlling growing conditions more precisely. If water and nitrogen are complementary inputs, the presence of irrigation should increase the rate of nitrogen application. Soil moisture is also controlled for by soil percolation rate, which is a function of soil texture and precipitation. The use of biotech seed is driven by the associated cost reductions from the technology's herbicide, pest, or fungus resistance. I also include a dummy variable representing whether the corn crop was grown for silage or corn.

The expanding production of ethanol, primarily with corn as the feedstock, has fueled non-trivial growth in corn prices over the past decade. While ethanol production has taken place in the United States for quite a while, the average rate of growth in ethanol production since 2000 has been 24%. In 2001, 1.8 million gallons were produced, but in less than ten years the volume has increased to 13.2 million gallons (Renewable Fuels Association, 2010). A recent estimate by Babcock and Fabiosa (2011) suggests ethanol demand increased the price of corn on average by 39% between the years 2006 and 2009. A report by the Congressional Budget Office (2009) estimates that the portion of corn demand stimulated by ethanol production raised the price by as much as 47%, a figure that represents more than $2/bu in today's corn market. While corn prices farmers report in the ARMS data embody these effects, leaving out a measure of ethanol production's influence on the farmer's production decisions could cause biases in the coefficients if ethanol production is correlated with other factors.

Using ethanol production data from the Renewable Fuels Association, I was able to create a variable that represents the production capacity within 125 km of each field in the ARMS sample. Table 3 presents a full list of covariates and summary statistics and makes it clear that the average corn field in the sample is located within 125 km of significant ethanol production.[12] In 2005, the Renewable Fuels Association reported a total production capacity of 3,643 million gallons per year, while the average amount of production capacity located within 125 kilometers of the sampled field was 3,149 million gallons, or 75% of total ethanol production.

Outcome Measures

I estimate the application rate for four different permutations of nitrogen fertilizer use. First, I estimate commercial nitrogen use by farmers who apply commercial nitrogen exclusively –a group that accounts for a 78% of the farmers in the sample. Second, I examine the rate of total commercial nitrogen use by all farmers, regardless of whether they used commercial nitrogen exclusively or in conjunction with manure. Third, I examine the sensitivity of commercial nitrogen use by farmers who use manure with commercial nitrogen–a group that employs an imperfect substitute for commercial nitrogen. These farmers make up a minority of the sample, 22%. Finally, I examine the effect of our explanatory variables on total nitrogen application rate, which includes commercial nitrogen and manure. It should be noted that all of the farmers in the sample reported at least some use of commercial nitrogen fertilizer.

Results

Impact of Instruments on Endogenous Variables

I first present ordinary least squares estimates of the impact of the excluded instruments on nitrogen prices and N-soil test. Table 4 presents the regression estimates of equation (3), the first stage prediction of average precipitation rate on soil testing probability. For each of the four models, in line with *a priori* expectations of the instrument, I find that average annual precipitation rate had a negative and statistically significant effect on the probability of testing the soil for available nitrogen: a one inch increase in annual average precipitation reduces the probability of soil testing by 0.008-0.01%.

Table 5 presents results of equation (3), the prediction of commercial nitrogen price. Several of the instruments robustly influence the price of nitrogen. The measure of distance to New Orleans,

[12] The effect is likely captured by changes in the basis price of corn, rather than the overall price, because ethanol plants represent local demand conditions.

Table 3. Summary Statistics (N = 2,874)

Variable	Description	Mean	95% Confidence Interval	
Soiltestn	Nitrogen-soil test	0.21	0.18	0.24
Nprice	Nitrogen Price	0.33	0.32	0.33
Dealerrec	Dealer recommendation	0.32	0.29	0.35
Consultrec	Consultant recommendation	0.14	0.12	0.16
Extrec	Extension agent recommendation	0.04	0.02	0.05
Routine	Routine practice	0.28	0.26	0.30
op_age	OperatorâĂŹs age	52.69	52.11	53.27
Retired	Operator is retired from farming	0.04	0.03	0.06
College	Operator holds college degree	0.35	0.31	0.38
Infi	Net farm income	$44,865	$37,182	$52,548
Workoff	Derive income from off-farm work	0.38	0.35	0.41
Anycropins	Insurance participation rate	0.66	0.62	0.70
Prodvalpa	Production value per acre	$374.66	$339.75	$408.65
Landvalpa	Land value per acre	$1,604.66	$709.84	$2,499.47
Ownacre	Acres owned	328.69	301.10	345.63
Corn_p	Corn price	$2.11	$2.09	$2.13
Ethcap125	Ethanol production capacity within 125km (million gallons/year)	2,244.27	1,967.80	2,520.74
CCC	Straight corn rotation (3 years)	0.14	0.11	0.17
Nutrient plan	Nutrient plan in place	0.08	0.06	0.09
Irrigate	Irrigate the field	0.06	0.04	0.09
Wetland	Wetland on any part of the field	0.03	0.02	0.04
Tenure	Years farming	27.60	26.90	28.29
Spring	Spring fertilizer application	0.80	0.77	0.84
Tile	Field has tile drainage	0.36	0.32	0.39
Avgperc	Average soil percolation (annual inches)	3.92	3.75	4.099
Inc	Incorporated fertilizer	0.75	0.73	0.78
Inhibit	Fertilizer applied with inhibitor	0.07	0.05	0.09
GMO_corn	GMO corn	0.34	0.30	0.38
Yldgoal	Yield goal	174.20	166.96	181.43
Silage	Corn for silage	0.11	0.09	0.13
Livestock	Presence of livestock on the farm	0.57	0.55	0.60
Commercial N w/o manure	Commercial N users only (n = 2334)	129.72	125.67	133.77
Total Commercial N	Total commercial N use	118.42	114.42	122.42
Commercial N w/ manure	Commercial N use by manure users (n = 656)	77.23	70.60	83.87
Total N	Total commercial N and manure use	137.59	132.16	143.02

Notes: All prices are in 2005 dollars. Data are from the Agricultural Resource Management Survey, years 2001 and 2005.

an instrument meant to capture the impact of distance to the major ammonia import terminal, was positive and statistically significant in every case except when commercial nitrogen was applied in conjunction with manure. The result can be interpreted as an elasticity figure. In the case of exclusive users of commercial nitrogen, for every 10% increase in the distance to New Orleans, the price of nitrogen increases by 0.69%. The distance to the nearest ammonia production plant and capacity of

Table 4. Estimates of the Impact of Instrument on Soil Test: First-Stage Least Squares Estimates

IV model	Dependent Variable	Excluded Instruments	Coefficient (Std. Err.)	Model R2
Commercial nitrogen, non-manure users (N = 2,253)	Soil Test	Avg. Precipitation	-0.01***	0.23
			(2.10E-03)	
Total commercial nitrogen (N = 2,874)	Soil Test	Avg. Precipitation	-0.01***	0.21
			(1.90E-03)	
Commercial nitrogen in the presence of manure use (N = 621)	Soil Test	Avg. Precipitation	2.95E-03	0.19
			(5.50E-03)	
Total nitrogen (N = 2874)	Soil Test	Avg. Precipitation	-0.01***	0.21
			(1.90E-03)	

Notes: Numbers in parentheses are robust standard errors. Triple asterisks (***) represent significance at the 1% level. Data are from the Agricultural Resource Management Survey, years 2001 and 2005.

the closest three plants were also statistically significant. The coefficient representing the distance to the nearest ammonia plant suggests farmers pay more if they are closer to an ammonia production plant. The price effect of the distance to the nearest plant ranged from -0.31E-08 to -0.32E-08, implying an elasticity of -0.010. The capacity of the nearest plant, on the other hand, predicts that prices fall as the capacity of the plant increases, although the effect is very small. Because of large standard errors, I cannot reject the null hypothesis of no effect.

The coefficients on the instrument representing the total capacity of the three nearest plants are all positive, suggesting the price of nitrogen increases as concentration of capacity increases in the field's vicinity. The capacity of the closest three plants has an implied elasticity figure of 0.054 to 0.065. Two points can be made about the results of the instrument. First, the results suggest the market is less than competitive at the local level. Second, the capacity instrument may not precisely represent actual production. Thus, there may be some degree of error in the measure; however, actual production is very likely to be positively correlated with capacity.

Instrumental Variable Results

Table 6 presents IV regression results. Soil nitrogen testing has a statistically significant impact on nitrogen application rates in each model except the limited sample of manure users. In fact, for the outcome measure total nitrogen rate, the coefficients imply that conducting a soil test results in the use of 60% less total nitrogen. In the case of commercial nitrogen, those who tested the soil applied nearly 80 pounds per acre less than those who did not, *ceteris paribus*. Others have found soil tests to have a similar effect (Wu and Babcock, 1998; Musser et al., 1995).

To help interpret the results, it would be of interest to know who conducted the soil test. In some cases it is performed by the dealer as part of a fertilizer purchase, in other cases it is paid for by the farmer or provided free of charge. Issues such as a principal-agent problem could also arise, but due to a lack of data, I am not able to determine who conducted the test. However, results show that the difference in rate between testing and non-testing can be quite large.

The estimates confirm the importance that information and its sources play in the fertilizer management decision. Farmers who relied on the recommendation of a fertilizer dealer applied 11-17% more nitrogen per acre than farmers not considering dealers' advice. In contrast, Lawley, Lichtenberg, and Parker (2009) do not find the rate recommendation of a fertilizer dealer to be

Table 5. Estimates of the Impact of Instruments on N price: First-Stage Least Squares Estimates

IV model	Dependent Variable	Excluded Instruments	Coefficient (Std. Err.)	Model R2
Commercial nitrogen, non-manure users (N = 2,253)				
	N Price	Dist. to New Orleans, LA	0.07***	0.10
			(0.02)	
		Dist. nearest ammonia plant	-3.22e-08***	
			(1.04e-08)	
		Cap. of closest ammonia plant	-4.90E-05	
			(-4.70E-05)	
		Cap. total three ammonia plants	5.00E-05*	
			(-2.50E-05)	
Total commercial nitrogen (N = 2,874)				
	N Price	Dist. to New Orleans, LA	0.08***	0.09
			(0.02)	
		Dist. nearest ammonia plant	-3.12e-08***	
			(9.66e-09)	
		Cap. of closest ammonia plant	-5.00E-05	
			(4.29E-05)	
		Cap. total three ammonia plants	6.00E-05**	
			(2.46E-05)	
Commercial nitrogen in the presence of manure use (N = 621)				
	N Price	Dist. to New Orleans, LA	0.07	0.09
			(0.05)	
		Dist. nearest ammonia plant	-2.39e-08	
			(2.56e-08)	
		Cap. of closest ammonia plant	-1.30E-04	
			(1.14E-04)	
		Cap. total three ammonia plants	3.92E-05	
			(9.00E-05)	
Total nitrogen (N = 2,874)				
	N Price	Dist. to New Orleans, LA	0.08***	0.09
			(0.02)	
		Dist. nearest ammonia plant	-3.12e-08***	
			(9.66e-09)	
		Cap. of closest ammonia plant	-5.00E-05	
			(4.29E-05)	
		Cap. total three ammonia plants	6.00E-05**	
			(2.46E-05)	

Notes: Numbers in parentheses are robust standard errors. Double and triple asterisks (**, ***) represent significance at the 5% and 1% level. Data are from the Agricultural Resource Management Survey, years 2001 and 2005.

statistically significant. In terms of a practical effect on the field, the magnitudes of the coefficients on the outside recommendation variables are relatively large. As in Lawley, Lichtenberg, and Parker (2009), the crop consultant played a larger role than the fertilizer dealer. The impact of a crop consultant's recommendation was even greater than the impact of a dealer's recommendation. These farmers applied 31-34% more nitrogen per acre than those who did not, except in the case of commercial nitrogen applied in the presence of manure, in which case it is not possible to make any inference from the estimate.

Having a nutrient management plan is thought to help farmers with their nitrogen use efficiency; however, for each of the four outcome variables, I do not reject the null hypothesis of no effect, and thus cannot make an inference about the variable's impact on rate of nitrogen applied.

Applying nitrogen with an inhibitor was associated with higher rates of application, and the effect is strongest for farmers who use a combination of manure and commercial nitrogen (70%). These results indicate that an inhibitor reduces the risk of early release (or increases the likelihood of nitrification coinciding with plant need), and as a result, encourages a higher rate of application. Commercial nitrogen application rate was also affected, though to a lesser extent. The results suggest inhibitors are a risk-reducing technology that could produce an adverse incentive whereby producers will apply more at the margin if they know it is more likely to affect yield.

Table 7 reports the own-price elasticities of quantity demanded for nitrogen fertilizer and tests of the instruments. Evidence suggests that rising fertilizer prices may have made farmers relatively more sensitive to price. Column 1 presents elasticity estimates for commercial nitrogen by farmers who use nitrogen fertilizer exclusively. The elasticity estimate is -1.87. When I expand the sample to include farmers who applied commercial nitrogen and manure (column 2), the estimated elasticity is -1.67. I do not reject the null at the 5% level of significance for either figure. To put the figure in context, at the mean amount of total commercial nitrogen, a 10% change in price would result in a decrease by nearly 19 pounds per acre.[13] The integrity of the elasticities estimated with IV relies on the relative strength and reliability of the instruments. It is argued that a low correlation between the instrument and the endogenous variable is a sign of a weak instrument. Weak instruments, in turn, can lead to problems in the second stage of the estimation process, including inconsistent IV estimates and estimates that are biased toward ordinary least squares (Bound, Jaeger, and Baker, 1995). The diagnostic evidence from table 7 for the F-statistics on the identifying instruments and partial R-squares indicates strong correlation between the instrument and prices for each sample, except in the limited sample of manure users. In the three large samples estimating commercial application rates and total nitrogen applications rates, the partial R-squares on the instruments range from 0.0039 to 0.0133 and the F-statistics are near or greater than 10, a rule of thumb threshold for acceptable finite-sample properties; however, diagnostic evidence shows the instruments in the IV model estimating the quantity demanded for commercial nitrogen by manure users are unreliable.

Tests for the suitability of IV are also examined in table 7. I use an augmented regression suggested by Hausman (1979) to test the hypothesis that least squares is a consistent estimator of the model. The test involves regressing the dependent (quantity demanded) variable on the exogenous variables in the IV model and the error component from the first stage. The Durban-Wu-Hausman test statistics suggests I should reject OLS as a consistent estimator of nitrogen demand (p-values < 0.0001), except again in the case where the sample is limited to farmers who use manure with commercial nitrogen.[14]

I test overidentifying restrictions with a Hansen *J* statistic as a means of determining whether the set of instruments is jointly correlated with the disturbance term in the second stage equation. For each model I do not reject the null, except again for farmers who use manure with commercial nitrogen, which indicates the instruments are at least jointly independent of the decision to apply nitrogen, except through their effect on the probability of conducting a soil test and nitrogen prices.

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[13] The mean total commercial nitrogen application rate in our sample was 118.42 lbs/acre.

[14] Although the test statistic is not rejected because the instruments perform poorly in the case of the manure users, I cannot definitively conclude that OLS is the "correct" estimator to use.

Table 6. IV Estimates of Nitrogen Application Rate

Variable	Commercial nitrogen: non-manure users	Std. Err.	Total Commercial Nitrogen	Std. Err.	Commercial nitrogen: only manure users	Std. Err.	Total Nitrogen (manure & non-manure users)	Std. Err.
Soiltestn	−0.70	0.41	−1.18***	0.49	0.77	1.20	−0.93**	0.43
Lognprice	−1.87**	0.84	−1.67**	0.76	−0.74	1.70	−1.15	0.69
Dealerrec	0.11**	0.05	0.16***	0.06	0.10	0.10	0.14***	0.05
Consultrec	0.17	0.10	0.29***	0.11	−0.03	0.26	0.27***	0.10
Extrec	0.03	0.10	0.13	0.10	0.17	0.17	0.12	0.08
Routine	−0.17**	0.08	−0.19***	0.08	−0.04	0.11	−0.14**	0.07
Op_age	−0.01***	0.00	−0.01***	0.00	0.01	0.01	−7.28E-03***	2.53E-03
Retired	0.12	0.10	0.12	0.11	0.10	0.27	0.01	0.09
College	0.03	0.04	0.04	0.04	0.04	0.13	0.01	0.04
Infi	5.94E-08	6.76E-08	6.00E-08	5.75E-08	1.12E-07	1.46E-07	3.75E-08	5.50E-08
Workoff	−0.08**	0.04	−0.08	0.04	−0.10	0.09	−0.11***	0.038
Anycropins	0.04	0.06	0.10	0.06	0.02	0.11	0.10***	0.051
Prodvalpa	−1.97E-05	4.02E-05	−3.73E-05	3.11E-05	−8.29E-05***	4.09E-05	3.38E-05	2.38E-05
Landvalpa	−8.76E-08	5.14E-07	−5.92E-07	8.01E-07	−3.64E-05	3.04E-05	−1.12E-06	8.42E-07
Ownacre	3.07E-05***	1.52E-05	3.52E-05***	1.72E-05	−1.03E-04	6.36E-05	2.50E-05	1.52E-05
logcorn_p	0.01	0.05	0.05	0.05	−3.06E-03	0.14	0.04	0.05
Ethcap125	−6.36E-06	5.31E-06	−1.01E-05	6.38E-06	3.28E-06	2.87E-05	−8.56E-06	5.34E-06
Ccc	0.06	0.06	0.10	0.06	0.20	0.10	0.10	0.05
Wetland	−0.14	0.13	−0.09	0.12	−0.08	0.35	−0.05	0.10
Nutrplan	0.14	0.08	0.03	0.09	−0.33	0.18	0.15	0.08
Irrigate	0.49***	0.11	0.55***	0.12	−0.22	0.44	0.54***	0.10
Tenure	0.01***	2.49E-03	4.68E-03	2.71E-03	2.88E-03	0.01	3.15E-03	2.37E-03
Spring	0.03	0.05	0.03	0.05	0.01	0.16	0.03	0.04
Tile	0.14***	0.05	0.15***	0.05	−0.05	0.12	0.15***	0.05
Avgperc	0.01	0.01	2.37E-04	0.01	0.01	0.02	0.01	0.01
Inc	0.09	0.06	0.07	0.06	0.11	0.10	0.08	0.05
Inhibit	0.07	0.06	0.21***	0.06	0.53***	0.16	0.16***	0.06
GMO_corn	0.05	0.04	0.07	0.04	0.02	0.10	0.06	0.04
Yldgoal	6.12E-04***	2.41E-04	3.02E-04	1.82E-04	−2.49E-05	2.42E-04	1.01E-04	1.85E-04
Silage	−0.38***	0.11	−0.35***	0.08	−0.08	0.11	−0.09	0.08
Live	−0.11	0.06	−0.21***	0.07	−0.14	0.21	−0.10	0.06
Observations	2,253		2,874		621		2,874	
F-Statistic	5.48		9.63		5.60		6.93	
	[< 0.0001]		[< 0.0001]		[< 0.0001]		[< 0.0001]	

Notes: Standard errors are robust. Double and triple asterisks (**, ***) represent significance at the 5% and 1% level. Data are from the Agricultural Resource Management Survey, years 2001 and 2005.

Table 7. Elasticity of Nitrogen Application Rate

	Commercial Nitrogen: non-manure users	Total Commercial Nitrogen	Commercial Nitrogen: only manure users	Total Nitrogen (commercial nitrogen plus manure)
Coefficient	-1.87**	-1.67**	-0.74	-1.15
	(0.41)	(0.76)	(1.70)	(0.69)
Model *F*-test	5.48	9.63	5.60	6.93
	[<0.0001]	[<0.0001]	[<0.0001]	[<0.0001]
Partial R^2 for first-stage regressions				
Soiltest	1.33E-02	8.30E-03	5.70E-03	8.30E-03
LogNprice	3.90E-03	4.30E-03	4.30E-03	4.30E-03
F-test on identifying instruments				
Soiltest	10.30	9.27	1.48	9.27
	[<0.0001]	[<0.0001]	[0.0248]	[<0.0001]
LogNprice	9.75	11.21	1.24	11.21
	[<0.0001]	[<0.0001]	[0.357]	[<0.0001]
Hansen J Statistic (all instruments)	0.133	2.73	12.83	2.585
	[0.99]	[0.43]	[0.01]	[0.46]
Durbin-Wu-Hausman	27.17	27.65	0.799	14.48
	[<0.0001]	[<0.0001]	[0.696]	[0.0007]
Observations	2,253	2,874	621	2,874

Notes: Numbers in parentheses are robust standard errors. Double asterisks (**) represent significance at the 5% level. Data are from the Agricultural Resource Management Survey, years 2001 and 2005.

Policy Implications

If policymakers are interested in reducing nitrogen over-application or aligning nitrogen rates more closely with soil test recommendations, they could consider policies that prompt producers to effectively internalize the cost of their externalities from production. Although there are several ways to achieve reductions in application rates, a price mechanism, such as a tax, is an efficient means of aligning producers' cost with the true cost to society. As a policy instrument, a tax on inputs has some desirable characteristics and some drawbacks. First, a tax gives farmers flexibility in how they reduce emissions. Farmers face heterogeneous costs, and a tax allows them to tailor their input responses (nitrogen abatement) accordingly. In the case of nitrogen, an input tax directly affects application rate, the management decision with the largest impact on potential nitrogen losses. A tax does not require monitoring or enforcement, unlike a command-and-control approach, and a tax raises revenue. In return, such revenue could be used to offset the tax burden of crop producers who improve their nitrogen use efficiency or used to remedy damage cause by nitrogen losses.

Setting an optimal or Pigouvian tax in order to achieve a reduction in nitrogen application is exceedingly difficult, particularly given the lack of information about farmers' marginal cost functions and society's marginal damage function. However, it is possible to assess the change in price necessary to induce farmers to reduce their application rate to a level that is consistent with predicted crop needs and therefore minimize the likelihood of environmental losses. To address

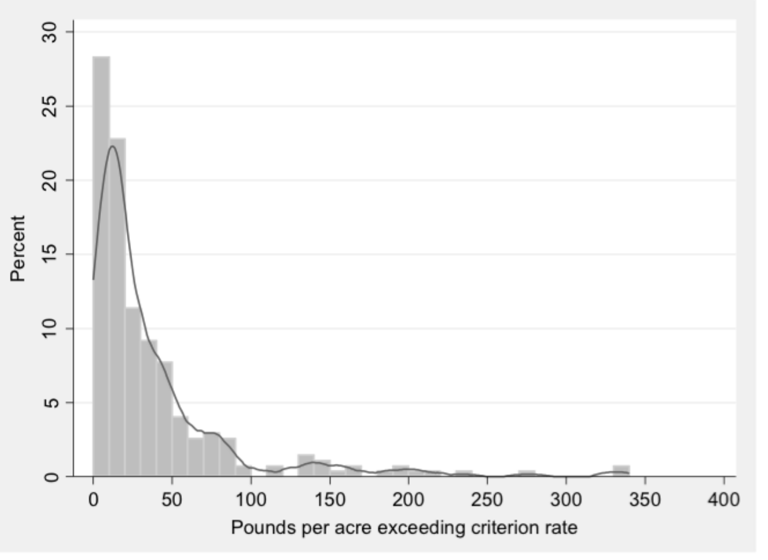

Figure 4. Distribution of Nitrogen Applied to 2005 Corn Exceeding Criterion Rate

Notes: Criterion rate is defined as 40% more than the assimilative capacity of the plant. The smooth line represents the kernel density estimated with an Epanechnikov kernel. Data are from the Agricultural Resource Management Survey, years 2001 and 2005.

excess nitrogen application, I focus on users who exceed recommended rates by the greatest amounts. I first estimate each field's criterion rate based on the crop's assimilative capacity, farmer's yield goal, and a margin of error for environmental losses, and then compare that figure with the actual application rate.[15]

Figure 4 displays the distribution of the nitrogen application rates that exceeded their criterion rate. Of the 76 million planted corn acres, 35% were treated with nitrogen at a rate exceeding the criterion rate (26.7 million acres), and farmers who exceeded their criterion rate had a mean rate of 185.5 lbs/acre. From the distribution depicted in figure 4, it is evident from the concentration of farmers near zero that most farmers who apply nitrogen at rates above their criterion rate are situated near their criterion threshold. In fact, 50% of farmers who exceed the criterion rate exceed it by 19 lbs/acre or less. This has implications for the ability of a tax to increase nitrogen use efficiency. Based on an estimated elasticity of -1.67 (total commercial nitrogen), if an input tax increased the price of nitrogen by 6.1 %, we would observe an improved rate of application on about 13.4 million of the 26.7 million over-treated acres of corn cropland.[16]

Seventy-five percent of heavy nitrogen users exceed the criterion rate by 43.4 lbs/acre or less, raising the price of nitrogen by 14% would therefore reduce cropland exceeding the criterion rate by 20 million acres. For context, the mean price of nitrogen fertilizer in 2005 was 33 cents/lb; therefore, a 6.2% change in the price is about 2 cents/lb, and a 14.4% change is less than 5 cents/lb.

Despite the relative simplicity of a tax, there are notable drawbacks. In particular, the incidence of the tax can have distributional consequences. Statutorily, the incidence of the tax could fall on nitrogen fertilizer producers; however, the economic incidence is likely to be shared by farmers. How much of the burden would be shared by farmers is dependent on the relative sensitivity of famers to

[15] The criterion rate is defined as a rate of nitrogen no greater than 40% above the amount of nitrogen removed with the crop at harvest, based on the stated yield goal. This approach is consistent with a more traditional approach for estimating nitrogen rate recommendations (Millar et al., 2010); it is also the criterion used by NRCS in their assessment of conservation practices in the Upper Mississippi Basin (U.S. Department of Agriculture, Natural Resources Conservation Service, 2010). Crop uptake coefficients are from NRCS (Lander, Moffitt, and Alt, 1998, table 3.1).

[16] Author's calculations using ARMS data.

price change and the supply elasticity of nitrogen: the more sensitive a farmer's quantity demanded for nitrogen is, the less a burden they bear, *ceteris paribus*. Based on the estimated elasticities in this research, farmers may shift part of the burden of the excise tax to the producer of fertilizer (Fullerton and Metcalf, 2002). While a factor tax on nitrogen may be welfare improving from society's point of view, ultimately, the tax will change the functional distribution of income.[17] The distributional impact may be mitigated if revenues raised by the tax are returned to farmers, for example, by supporting other conservation activities.

Ideally, a tax would be placed on nitrogen emissions that are the source of environmental problems; however, an input tax makes no distinction between fertilizer that is in excess or is meeting the rate criterion. A tax on nitrogen may also encourage the use of untaxed animal waste, resulting in no discernible change in nitrogen applications.

Conclusion

I use data from the USDA's Agricultural Resource Management Survey to investigate the impact that management practices and prices have on the amounts of nitrogen fertilizer applied at the field level. This research presents an innovative identification strategy using spatial variation in domestic ammonia production to estimate nitrogen prices. The price elasticity of quantity demanded for nitrogen fertilizer applied to corn ranges from -1.67 to -1.87. Further, self-reports from farmers signaled that they managed nitrogen application more carefully in order to account for higher nitrogen prices. Therefore, while policies that raise the price of nitrogen may have an effect on the quantity of nitrogen applied, they may also encourage better management techniques, such as timing application to better align with plant needs or using more precise application methods. IV estimates also show that soil testers use significantly less nitrogen fertilizer than non-testers, *ceteris paribus*. Estimates are robust and range from 65 to 83 pounds per acre, depending on the combination of nitrogen fertilizer used. If society is concerned about excessive nitrogen application, conservation policy design must consider how information and prices affect a wide range of farmer behavior and, ultimately, environmental outcomes.

[Received October 2010; final revision received September 2011.]

[17] In addition to an associated deadweight loss, factor taxes also have administrative costs. Whether the tax is welfare will depend on the size of these costs as well as benefits from the reducing nitrogen runoff.

References

Babcock, B. A. and J. F. Fabiosa. "The Impact of Ethanol and Ethanol Subsidies on Corn Prices: Revisiting History." 2011. CARD Policy Brief 11-PB 5, Center for Applied and Rural Economics, Iowa State University.

Bound, J., D. A. Jaeger, and R. M. Baker. "Problems with Instrumental Variables Estimation When the Correlation between the Instruments and the Endogenous Explanatory Variable is Weak." *Journal of the American Statistical Association* 90(1995):443–450.

Burkholder, J. M. and H. B. Glasgow. "*Pfiesteria* piscicida and Other *Pfiesteria*-like Dinoflagellates: Behavior, Impacts, and Environmental Controls." *Limnology and Oceanography* 42(1997):1052–1075.

Burrell, A. "The Demand for Fertilizer in the United Kingdom." *Journal of Agricultural Economics* 40(1989):1–20.

Carman, H. F. "The Demand for Nitrogen, Phosphorous and Potash Fertilizer Nutrients in the Western United States." *Western Journal of Agricultural Economics* 4(1979):22–32.

Cassman, K. G., A. Dobermann, and D. T. Walters. "Agroecosystems, Nitrogen-use Efficiency, and Nitrogen Management." *Ambio* 31(2002):132–140.

Chow, G. C. "Rational Versus Adaptive Expectations in Present Value Models." *Review of Economics and Statistics* 71(1989):376–384.

Congressional Budget Office. "The Impact of Ethanol Use on Food Prices and Greenhouse-Gas Emissions." 2009. Washington, DC.

Denbaly, M. and H. Vroomen. "Dynamic Fertilizer Nutrient Demands for Corn: A Cointegrated and Error-Correcting System." *American Journal of Agricultural Economics* 75(1993):203–209.

Dodds, W. K., W. W. Bouska, J. L. Eitzmann, T. J. Pilger, K. L. Pitts, A. J. Riley, J. T. Schloesser, and D. J. Thornbrugh. "Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages." *Environmental Science & Technology* 43(2009):12–19.

Fullerton, D. and G. E. Metcalf. *Tax Incidence*, vol. 4. 2002, 1787–1872.

Greene, W. H. *Econometric Analysis*. Upper Saddle River, NJ: Prentice-Hall International, 2000, 4th ed.

Griliches, Z. "The Demand for Fertilizer: An Economic Interpretation of a Technical Change." *Journal of Farm Economics* 40(1958):591–606.

Hansen, L. G. "Nitrogen Fertilizer Demand from Danish Crop Farms: Regulatory Implications of Heterogeneity." *Canadian Journal of Agricultural Economics* 52(2004):313–331.

Hausman, J. "Specification Tests in Econometrics." *Econometrica* (1979).

Heady, E. O. and M. H. Yeh. "National and Regional Demand Functions for Fertilizer." *Journal of Farm Economics* 41(1959):332–348.

Huang, W. "Impacts on Rising Natural Gas Prices on U.S. Ammonia Supply." 2007. U.S. Department of Agriculture, Economic Research Service Report, WRS-0702.

Just, R. E. "Risk Aversion under Profit Maximization." *American Journal of Agricultural Economics* 57(1975):347–352.

Lander, C., D. Moffitt, and K. Alt. "Nutrients Available for Livestock Manure Relative to Crop Growth Requirements." 1998. Resource Assessment and Strategic Planning Working Paper 98-1, U.S. Department of Agriculture, Natural Resources Conservation Service. Available online at www.nrcs.usda.gov/technical/NRI/pubs/nlweb.htm.

Lawley, C., E. Lichtenberg, and D. Parker. "Biases in Nutrient Management Planning." *Land Economics* 85(2009):186–200.

Millar, N., G. P. Robertson, P. R. Grace, R. J. Gehl, and J. P. Hoben. "Nitrogen Fertilizer Management for Nitrous Oxide (N$_2$O) Mitigation in Intensive Corn (Maize) Production: An Emissions Reduction Protocol for US Midwest Agriculture." *Mitigation and Adaptation Strategies for Global Change* 15(2010):185–204.

Musser, W. N., J. S. Shortle, K. Kreahling, B. Roach, W. C. Huang, D. B. Beegle, and R. H. Fox. "An Economic Analysis of the Pre-Sidedress Nitrogen Test for Pennsylvania Corn Production." *Review of Agricultural Economics* 17(1995):25–35.

Muth, J. F. "Rational Expectations and the Theory of Price Movements." *Econometrica* 29(1961):315–335.

Rabalais, N. N., R. E. Turner, and W. J. Wiseman. "Hypoxia in the Gulf of Mexico." *Journal of Environmental Quality* 30(2001):320–329.

Rajsic, P., A. Weersink, and M. Gandorfer. "Risk and Nitrogen Application Levels." *Canadian Journal of Agricultural Economics* 57(2009):223–239.

Randall, G. W. and D. J. Mulla. "Nitrate Nitrogen in Surface Waters as Influenced by Climatic Conditions and Agricultural Practices." *Journal of Environmental Quality* 30(2001):337–344.

Ray, S. C. "A Translog Cost Function Analysis of U.S. Agriculture, 1939-77." *American Journal of Agricultural Economics* 64(1982):490–498.

Renewable Fuels Association. "2010 Ethanol Industry Outlook: Climate of Opportunity." 2010. Washington, DC.

Roberts, R. K. and E. O. Heady. "Fertilizer Demand Functions For Specific Nutrients Applied To Three Major U.S. Crops." *Western Journal of Agricultural Economics* 7(1982):265–278.

Roosen, J. and D. A. Hennessy. "Tests for the Role of Risk Aversion on Input Use." *American Journal of Agricultural Economics* 85(2003):30–43.

Sheriff, G. "Efficient Waste? Why Farmers Over-Apply Nutrients and the Implications for Policy Design." *Review of Agricultural Economics* 27(2005):542–557.

Shumway, C. R. "Supply, Demand, and Technology in a Multiproduct Industry: Texas Field Crops." *American Journal of Agricultural Economics* 65(1983):748–760.

Trachtenberg, E. and C. Ogg. "Potential for Reducing Nitrogen Pollution through Improved Agronomic Practices." *Water Resources Bulletin* 30(1994):1109–1118.

U.S. Department of Agriculture, National Agricultural Statistics Service. "Agricultural Prices 2008 Summary." 2009.

U.S. Department of Agriculture, Natural Resources Conservation Service. "Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin." 2010.

U.S. Environmental Protection Agency. "Nitrates and Nitrites: Teach Chemical Summary." 2006. Available online at http://www.epa.gov/teach/chem_summ/Nitrates_summary.pdf.

U.S. Geological Survey. "The Quality of Our Nation's Waters–Quality of Water from Domestic Wells in Principal Aquifers of the United States, 1991-2004–Overview of Major Findings." National Water-Quality Assessment Program Circular, 1332. Reston, Virginia.

———. "Streamflow and Nutrient Delivery to the Gulf of Mexico for October 2008 to May 2009 (Preliminary)." 2009. Available online at http://toxics.usgs.gov/hypoxia/mississippi/oct_jun/index.html.

Weaver, R. D. "Multiple Input, Multiple Output Production Choices and Technology in the U.S. Wheat Region." *American Journal of Agricultural Economics* 65(1983):45–56.

Wu, J. and B. A. Babcock. "The Choice of Tillage, Rotation, and Soil Testing Practices: Economic and Environmental Implications." *American Journal of Agricultural Economics* 80(1998):494–511.

Yadav, S. N., W. Peterson, and K. W. Easter. "Do Farmers Overuse Nitrogen Fertilizer to the Detriment of the Environment?" *Environmental & Resource Economics* 9(1997):323–340.