IOWA STATE UNIVERSITY
Digital Repository

Retrospective Theses and Dissertations

Iowa State University Capstones, Theses and Dissertations

2008

Essays on fall fertilizer application

Mira Nurmakhanova
Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/rtd

Part of the Agricultural and Resource Economics Commons, Agricultural Economics Commons, and the Economics Commons

Recommended Citation

Nurmakhanova, Mira, "Essays on fall fertilizer application" (2008). *Retrospective Theses and Dissertations*. 15740.
https://lib.dr.iastate.edu/rtd/15740

This Dissertation is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.

Essays on fall fertilizer application

by

Mira Nurmakhanova

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Economics

Program of Study Committee:
Catherine L. Kling, Co-major Professor
Joseph A. Herriges, Co-major Professor
Bruce A. Babcock
Jinhua Zhao
Philip Dixon

Iowa State University

Ames, Iowa

2008

Copyright © Mira Nurmakhanova, 2008. All rights reserved.

UMI Number: 3330736

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI®

UMI Microform 3330736
Copyright 2008 by ProQuest LLC
All rights reserved. This microform edition is protected against
unauthorized copying under Title 17, United States Code.

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

TABLE OF CONTENTS

CHAPTER 1. OVERVIEW 1

CHAPTER 2. TIMING OF FERTILIZER APPLICATION: ENVIRONMENTAL IMPLICATIONS
- 2.1 Introduction 13
- 2.2 The Model 15
- 2.3 Estimation Details 17
- 2.4 Data 22
- 2.5 Results 26
- 2.6 Environmental Implications 27
- 2.7 Conclusions 38
- 2.8 Appendix 40
- 2.9 References 44

CHAPTER 3. DECISION ON TIMING OF FERTILIZER APPLICATION AND TILLAGE SYSTEM: IMPLICATIONS FOR NITROGEN PRODUCTIVITY
- 3.1 Introduction 51
- 3.2 Previous Literature 53
- 3.3 The Model 56
- 3.4 Estimation Details 59
- 3.5 Data 63
- 3.6 Results 68
- 3.7 Environmental Implications 70
- 3.8 Conclusions 78
- 3.9 Appendix 80
- 3.10 References 83

CHAPTER 4. CONTRACTING SPLIT FERTILIZER APPLICATION
- 4.1 Introduction 91
- 4.2 Previous Literature 93
- 4.3 The Model 94
- 4.4 Analysis of the Model 101
- 4.5 Empirical Application 105
- 4.6 Conclusions 113
- 4.7 Appendix 115
- 4.8 References 123

ACKNOWLEDGEMENTS 130

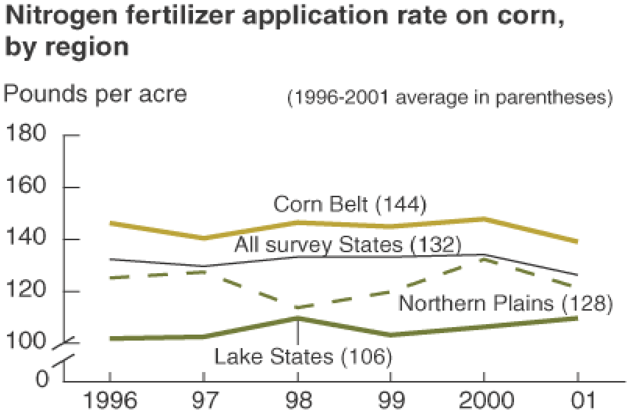
CHAPTER 1: OVERVIEW

Nitrogen is an essential plant nutrient and an adequate supply of nutrients is necessary for crop growth. Ideally, soil nutrients should be available in the proper amounts at the time the plant can use them. Estimates of crop absorption of nitrogen range from 25% to 70% and generally vary as a function of plant growth, health, the method, and timing of nitrogen application (Blackmer, 2000). The amount of nitrogen fertilizer applied in excess of the amount taken up by the plant fertilized is a main source of nitrogen loss. Unused nitrogen can be immobilized, denitrified, washed into surface water, or leached into groundwater (Huang and Uri, 1995; Huang, Hewitt, and Shank, 1998; Huang *et al*., 1998; Dinnes *et al*., 2002; Randall and Schmitt, 1998; Uri, 1998; Blackmer, 1995). As a result, relatively heavy use of nitrogen and some other fertilizers can lead to soil acidification, changes in soil properties, and off-site environmental problems.

Public concern over water quality increased a focus on agriculture as a potential source of surface and groundwater quality problems. Nitrate nitrogen concentrations in excess of 10 mg per liter in drinking water may pose risks to humans and livestock (USDA, 1991) and have cost some places millions of dollars for their removal or to provide alternate drinking water sources. For example, Des Moines, Iowa spent over $4.8 million for nitrate removal from drinking waters between 1991 and 1999 (Dinnes *et al*., 2002). The presence of nitrates in drinking water can cause potentially fatal infant methemoglobinemia (blue baby syndrome). Nitrates are also linked to nitrosamine, a potent carcinogen which can affect a wide range of organs in many animal species (Huang and Uri, 1999; Johnson, Adams, and Perry, 1991; Yadav, Peterson, and Easter, 1997). Moreover, nitrate is the principal nutrient related to hypoxia in the Gulf of Mexico. This zone of low dissolved oxygen covers an area from 13,000 to 20,000 km^2 off the shore of Louisiana. It has been shown to be due to excess nutrients, particularly nitrate nitrogen, being transported to the Gulf from the Mississippi River Basin (Mitsch *et al*., 2001).

The Pew Oceans Commission on June 5, 2003 called for the federal government to force farmers to cut pollution running into waterways or risk losing federal aid (http://www.pewoceans. org/). The commission's report says that problems such as ocean dead zones will not improve unless farmers try to follow the Clean Water Act. Some of the statistics show that Iowa and Illinois are two of the biggest sources of nitrogen running down the Mississippi River to the Gulf of Mexico (US Geological Survey, http://toxics.usgs.gov/hypoxia/). They account for up to 35 percent of the nitrogen washing down the Mississippi River watershed, which covers 41 percent of the lower 48 states, while Corn Belt states apply most of nitrogen fertilizer (see Fig. 1). As a consequence, understanding the determinants of fertilizer and pesticide use is an important element in being able to solve the problem.

Figure 1.1



Nonpoint loss of nitrogen from fields to water resources, though, is not caused by any single factor. Rather, it is caused by a combination of factors, including tillage, drainage, crop selection, soil organic matter levels, hydrology, and temperature and precipitation. Therefore, a strategy to reduce contamination of water resources from crop production includes identifying appropriate management practices to minimize leaching and runoff of nitrogen. Practices for reducing nitrogen loss include improved timing of nitrogen application at appropriate rates, using soil tests and plant monitoring, diversifying crop rotations, including a cover crop, reducing tillage, precision farming, postharvest management of fields, etc. (Hatfield and Cambardella, 2001; Uri, 1998; Dinnes *et al*., 2002). These practices often referred to as “best management practices” (BMPs) and are typically developed to increase the efficiency with which nutrients, pesticides, and irrigation water are used.

The agronomic fertilizer recommendations for a field depend on the crop to be grown, anticipated yield goal, previous crop, and soil test results (Shapiro *et al.,* 2003; Iowa State University Extension, 2007). Recommended nitrogen application rates should be adjusted to account for nitrogen supplied by previous legume crops, manure, other organic wastes, or residual soil nitrate. If farmers do not credit other sources of nitrogen, they may end up applying more nitrogen than is agronomically necessary. When fertilizers are overapplied, the total amount of plant nutrients available to growing crops not only exceeds the need of the plant but the economic optimum as well. Yadav, Peterson, and Easter (1997) using experimental data for farm sites in southeastern Minnesota empirically estimated the production function and profit maximizing level of nitrogen application. Their results showed that both the current recommendation rate and farmers’ use of nitrogen exceeded the profit maximizing level of nitrogen in the region suggesting that recommended rate needs to be revised and made more site specific. Additionally, research from across the Corn Belt indicated that economic optimum nitrogen rate (EONR) does not vary according to yield level (Sawyer and Nafziger, 2005). These issues increased uncertainty regarding current nitrogen rate recommendations. In recent years nitrogen recommendation systems have become more diverse across states in the Corn Belt moving away from yield goal as a basis of nitrogen rate decisions in some states to other methods such as cropping system (Iowa) or soil specific yield potential (Wisconsin) (Sawyer and Nafziger, 2005; Sawyer and Nafziger, 2006).

Time of nitrogen application studies have been reported extensively in the literature. The general conclusion among researchers is that nitrogen fertilizer should be applied nearest to the time it is needed by the crop, i.e., side-dressed several weeks after corn emergence (Huang *et al.*, 2000; Huang, Hewitt, and Shank, 1998; Fuglie and Bosch, 1995; Bosch, Cook, and Fuglie*,* 1995). Nitrogen fertilizer, however, is typically applied to plant in fall, early spring (spring pre-emergent fertilization) and during the growing season (spring post-emergent fertilization). Generally, farmers practice single or split fertilizer applications. According to results of the analysis of 1996 ARMS data for U.S. corn farms and producers, applying all nitrogen at or after planting was used on 30 percent of the corn acreage (Christensen, 2002). Data also show that nitrogen fertilizer was applied before planting, either in the fall, the spring, or both, on 42 percent of the total acreage. All the nitrogen was applied in the fall to 13 percent of total acreage, but to almost 20 percent of the acreage in the Corn Belt. Thirty percent of all corn acreage received 100 percent of the nitrogen at or after planting, but this ranged from 45 percent in the Lake States to 24 percent in the Corn Belt. According to Dinnes *et al*. (2002) typical nitrogen fertilizer management for corn production in the subhumid Midwest currently consists of a single preplant application, usually in fall before the year that corn is grown. Table 1.1 contains data on timing of fertilizer application in U.S. for 1990-1997 period while Table 1.2 presents data for timing of fertilizer application by region in 1996 (http://www.ers.usda.gov/Briefing/ AgChemicals/nutrient mangement.htm). From data provided in these tables it is obvious that most of farmers still rely on pre-planting fertilizer applications.

Table 1.1. Timing of Fertilizer Application in U.S. 1990-1997.

Nitrogen application timing:	Year							
	90	91	92	93	94	95	96	97
Fall before planting	27	26	23	20	27	30	22	27
Spring before planting	57	50	53	51	54	52	54	51
At planting	44	48	47	48	43	42	43	44
After planting	26	31	31	35	27	29	33	30

Table 1.2. Timing of Fertilizer Application by Region in 1996.

Nitrogen application timing:	Corn Belt	Lake States	Plains States	Southeast	All
All in fall	19	5	6	0	13
None at/after planting	32	14	33	28	28
Less than 50% at/after planting	9	21	19	11	14
50-99% at/after planting	15	7	12	22	13
All at/after planting	24	45	27	38	30

For both agronomic and environmental reasons, spring post-emergent application of nitrogen fertilizer is frequently superior to fall and spring pre-emergent applications because less loss of nitrogen occurs in the one to three months between application and nitrogen uptake. Field experiments show that for certain types of soil, application of nitrogen fertilizer after planting can be more effective than before planting, including both fall and spring pre-emergent fertilizer applications, in reducing nitrogen losses. Nitrogen runoff may occur either between two agricultural seasons (in winter), or after early nitrogen application before the growing season (in the spring). Study of Balkcom *et al.* (2003) linked high nitrate concentrations in Iowa rivers to areas of intensive row crop production. Results showed that early-season rainfall and associated nitrate losses were major factors affecting nitrogen concentrations in soils. In some locations, a large part of the nitrogen may be lost if it is applied too long before the crop is planted, particularly if applied the previous fall before soil temperature drops to below 50° F. Fall application of nitrogen increases the loss of nitrogen through denitrification, it also gives nitrogen time to leach through the root zone and into groundwater or subsurface drainage tile. As a result, fall-applied nitrogen is usually 10 to 15 percent less effective than spring-applied nitrogen. The relative effectiveness is largely determined by soil characteristics and climatic conditions, and, therefore, varies substantially among locations and years. According to Blackmer and Sanchez (1988), 50 to 60 percent of fall applied nitrogen fertilizer is lost from the surface soil through several of the pathways that lead to nitrogen loss from the soil. In the research of Randall and Mulla (2001) nitrogen was applied in the fall (early November) and spring (late April) for continuous corn to determine the effect of nitrogen application time and rate on nitrate losses to subsurface drainage and corn yields in Minnesota. Corn yields from the late fall application averaged 8 percent lower than with spring application. Moreover, annual losses of nitrogen in the drainage water averaged 36 percent higher with fall application compared to spring application. Torbert *et al.* (2001) also reported 30 percent yield loss with fall fertilizer application compared with fertilizer application at planting. An 8-years study reported by Vetsch and Randall (2004) illustrated the large year-to-year effect of climatic conditions, but when averaged across years, nitrate losses from a corn–soybean rotation in Minnesota were reduced 17 percent by applying nitrogen in the spring compared with late in October. All this shows that changing the time of a single preplant fertilizer application from fall to spring could significantly decrease nitrogen loss and increase fertilizer use efficiency.

However, recent trends in agriculture which include increased farm size, more farmers with off-farm jobs (USDA-NASS; 1997, 1992) have left less time for farmers to sidedress nitrogen. Therefore, many corn growers, especially in the northern part of the Corn Belt (i.e., northern Iowa and southern Minnesota), still apply nitrogen in the fall and early spring because they usually have more time, potential for soil compaction following harvest is generally less, nitrogen fertilizer prices are often lower, and weather and soil conditions are generally more favorable (Randall and Schmitt, 1998; Dinnes *et al*., 2002). The opportunity cost of labor may be significantly higher during the late spring and growing season than during the fall. Spring rainfalls can result in very wet soils and prevent or delay nitrogen fertilizer applications. Consequently, uncertain weather conditions may shorten the time in which fertilizer can be applied during the growing season, increasing the risk of yield loss from inadequate nitrogen availability. Such risk is magnified for farmers with shorter growing seasons.

Additionally, there are some events such as bad weather that can reduce a crop's capacity to absorb nutrients. Also, unobservable processes such as leaching, denitrification, uptake in previous crops, and gain from nitrogen-fixing crops and manure application affect the availability of soil nutrients. As a result, the farmers' nutrient application may be affected by his/her perception of the yield risk, especially in the case of nitrogen, the most mobile nutrient applied to crops. Several studies have shown that uncertainty about soil nitrate levels may cause farmers to use chemical nitrogen fertilizer as a risk reducing input (Babcock, 1992; Musser *et al*., 1995; Lambert, 1990, Feinerman, Choi, and Johnson, 1990; Bontem and Thomas, 2000; Huang, Hansen, and Uri, 1994).

Babcock (1992) showed that soil nitrogen and weather uncertainty could result in expected profit-maximizing nitrogen applications 36% higher than under certainty. Feinerman, Choi, and

Johnson (1990) tested the hypothesis that excess fertilizer application at planting is used to insure against weather conditions not permitting a later application. They found that risk aversion leads to heavier reliance on early applications. For Iowa corn, risk aversion can lead to 3.2% increase in total applications. Huang, Hansen, and Uri (1994) also found that to insure against the risk of being unable to apply fertilizer during the growing season, risk-averse farmers apply more fertilizer prior to planting. They estimate that the impact of risk aversion on split fertilizer application decision for Iowa corn can almost triple nitrogen applications relative to risk-neutral levels. Bontem and Thomas (2000) considered a production model of sequential nitrogen application under risk. They estimated that risk premium and value of information (possibility for farmers to process information) account for 30 percent of fertilizer cost for Midwest corn producers. All these studies showed substantially higher fertilizer application rates whenever farmers faced any kind of uncertainty whereas the magnitude of extra fertilizer application was higher for risk-averse farmers compared to neutral ones. Spring rainfall patterns can result in very wet soils and prevent or delay nitrogen fertilizer applications. This risk is very real, therefore, despite the opportunities to increase nitrogen use efficiency and decrease loss of nitrogen through drainage waters, many farmers continue fall fertilizer applications to minimize real and perceived risk.

There are several reasons why farmers use crops rotation: (1) improve fertility by including nitrogen-fixing legumes in crop rotations, reducing the subsequent need for commercial nitrogen fertilizer, (2) control insects, diseases, and weeds, (3) reduce soil erosion and related loss of soil nutrients and moisture, (4) increase water-holding capacity of the soil through increased organic matter, (5) reduce the water pollution often associated with runoff and leaching, and (6) promote crop diversification to provide an economic buffer against price fluctuation for crops and production inputs (Christensen, 2002; Uri, 1998; Bosch and Pease, 2000; Riedall *et al.*, 1998). Cropping patterns adopted by corn farmers vary by region. Corn-soybean rotations and continuous corn are the most widespread, they were practiced on 75 percent of the total non-irrigated acres. According to results of the analysis of

1996 ARMS data for U.S. corn farms and producers, a corn-legume rotation was used on almost 60 percent of the 1996 corn acres (Christensen, 2002). Continuous corn was the rotation on 19 percent of the acreage. Use of a corn-legume rotation was highest in the Corn Belt, on 82 percent of the acreage, reflecting the common corn-soybean rotation used in this region. Most of the continuous corn production on nonirrigated acreage took place in the Corn Belt and Plains States, with 57 and 29 percent of the total U.S. corn acreage, respectively, farmed in this pattern. The Corn Belt is the leading region for the corn-soybean-corn pattern on nonirrigated corn acreage (with 68 percent of the total U.S. nonirrigated corn acreage in this rotation).

Studies show relatively high nitrate–nitrogen concentrations in subsurface drainage from row crops such as corn and soybeans; lower concentrations characterize perennial crops such as alfalfa or grass. Including legume crops in rotations has been shown to decrease nitrate losses (Randall et al., 1997; Baker and Melvin, 1994; Weed and Kanwar, 1996). Legumes, such as soybeans and alfalfa, sequester nitrogen from the atmosphere through nitrogen fixation and are used to provide fixed-nitrogen as a substitute for fertilizer-nitrogen. Differences in fertilizer management between annual and perennial cropping systems also impact their relative nitrate–leaching potentials. Typically, perennial cropping systems receive less tillage and nitrogen fertilizer than do annual cropping systems. In Iowa, Baker and Melvin (1994) reported much lower nitrate-nitrogen concentrations for alfalfa than for corn or soybean. Weed and Kanwar (1996) found higher nitrate nitrogen losses from plots planted to continuous corn compared with a corn–soybean rotation in Iowa. Also, in Minnesota, Randall et al. (1997) found that nitrate-nitrogen concentrations in drainage water from alfalfa fields were 37 and 35 times lower than in drainage water from corn and soybean fields, respectively. In summary, these studies showed substantially higher nitrate nitrogen concentrations in row crops, especially continuous corn, compared with perennial crops.

In addition to reduced amount of nitrogen fertilizer applied by farmers, rotation was shown to affect crop yields. In many studies corn yields were significantly higher under corn-soybean rotation than with continuous corn practice (Kanwar *et al.,* 1997; Riedell *et al.,* 1998). Therefore, one approach to decrease the use of nitrogen fertilizers is to adopt a fertilizer reducing farming practice, such as a crop rotation in which a legume crop (soybeans, alfalfa) is rotated with a non-legume crop (corn). Adoption of this sort of crop rotation can reduce the residual nitrogen in the soil through a reduction in the frequency and amount of nitrogen fertilizer applied on a field while increasing crop yields. Nitrogen credits from rotating corn with legume crops can range from about 45 kg per ha for soybeans to 170 kg per ha for alfalfa. In such cases this credit will suggest that no nitrogen fertilizer is required.

References

[1] Babcock, B. A. “The Effect of Uncertainty on Optimal Nitrogen Application”. *Review of Agricultural Economics*. 14 (1992): 271-280.

[2] Baker, J.L., and S.W. Melvin. ”Chemical Management, Status, and Findings”. *In* Agricultural drainage well research and demonstration project—Annual report and project summary. Iowa Dep.of Agric. and Land Stewardship, Des Moines. 1994. 27–60.

[3] Balkcom, K. S., A. M. Blackmer, D. J. Hansen, T. F. Morris, and A. P. Mallarino. “Testing Soils and Cornstalks to Evaluate Nitrogen Management on the Watershed Scale”. *Journal of Environmental Quality* 32(2003): 1015-1024.

[4] Blackmer, A.M. “Bioavailability of Nitrogen”. In M. E. Sumner (ed.) *Handbook of soil science*. CRC Press. Boca Raton. FL. 2000. D3-D18.

[5] Blackmer, A.M. “Losses of Fall-Applied Nitrogen”. In *Proc. Annual Integrated Crop Management Conference.* Iowa State University. Ames, IA. 29-30 Nov. 1995. 55-59.

[6] Blackmer, A. M., C. A. Sanchez. “Response of Corn to Nitrogen-15-Labeled Anhydrous Ammonia with and without Nitrapyrin in Iowa”. *Agronomy Journal*. 80 (1988): 95–102.

[7] Bontems, P., A. Thomas. “Information Value and Risk Premium in Agricultural Production: The Case of Split Nitrogen Application for Corn”. *American Journal of Agricultural Economics*. . 82:1 (2000): 59-70.

[8] Bosch, D. J., Z. L. Cook, K. O. Fuglie. “Voluntary versus Mandatory Agricultural Policies to Protect Water Quality: Adoption of Nitrogen testing in Nebraska”. *Review of Agricultural Economics*. 17 (1995): 13-24.

[9] Bosch, D. J., J. W. Pease. “Economic Risk and Water Quality Protection in Agriculture”. *Review of Agricultural Economics*. 22 (2000): 438-463.

[10] Christensen, L. A. “ Soil, Nutrient, and Water Management Systems Used in U.S. Corn Production”. *USDA. Agriculture Information Bulletin* (No.774). 2002.

[11] Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. "Nitrogen Management Strategies to Reduce Nitrate Leaching in Tile-Drained Midwestern Soils". *Agronomy Journal*. 94 (2002): 153-171.

[12] Feinerman, E., E. K. Choi, S. R. Johnson. "Uncertainty and Split Nitrogen Application in Corn Production". *American Journal of Agricultural Economics.* 72 (1990): 975-984.

[13] Fuglie, K.O., D.J. Bosch. "Economic and Environmental Implications of Soil Nitrogen Testing: A Switching-regression Analysis". *American Journal of Agricultural Economics*. 77 (1995): 891-900.

[14] Johnson, S. L., R. M. Adams, G. M. Perry. "The On-farm Costs of Reducing Groundwater Pollution". *American Journal of Agricultural Economics.* 73 (1991): 1063-1073.

[15] Hatfield, J.L., C. A. Cambardella. "Nutrient Management in Cropping Systems. *In* J. McFarland and M. Sanderson (ed.) Integrated management of land application of animal waste. American Society of Agricultural Engineering. St. Joseph, MI. 2001.

[16] Huang, W., L. Hansen, N. D. Uri. "The Application Timing of Nitrogen Fertilizer". *Water, Air, and Soil Pollution,* 73 (1994): 189-211.

[17] Huang, W., R.G. Heifner, H. Taylor, and N. D. Uri. "Timing Nitrogen Fertilizer Application to Reduce Nitrogen Losses to the Environment". *Water Resource Management.* 14 (2000): 35-58.

[18] Huang, W., T.I. Hewitt, and D. Shank. "An Analysis of On-Farm Costs of Timing N Applications to Reduce N Losses". *Journal of Agricultural and Resource Economics.* 23:2 (1998): 445-467.

[19] Huang, W., L., R. W. Keim, Y. Lu, N. D. Uri, T. Kelley. "The Impact of Nitrogen Carryover Effect on Economic Activity and the Environment". *Environmental Geology.* 34 (1998): 116-127.

[20] Huang, W., N. D. Uri. "A Note on Nitrogen Fertilizer Application Timing". *Applied Mathematical Modeling.* 19 (1995): 35-58.

[21] Huang, W., L. Hansen, N. D. Uri. "The Application Timing of Nitrogen Fertilizer". *Water, Air, and Soil Pollution.* 73 (1994): 189-211.

[22] Huang, W., N. D. Uri. *The Economic and Environmental Consequences of Nutrient Management in Agriculture*. Nova Science Publishers, Inc. 1999.

[23] Iowa State University Extension. "Nitrogen Fertilizer Recommendations for Corn in Iowa". 2007. (online: http://www.extension.iastate.edu/Publications/PM1714.pdf)

[24] Kanwar, R. S., T.S. Colvin, D. L. Karlen. "Ridge, Moldboard, Chisel, and No-Till Effects on Tile Water Quality beneath Two Cropping Systems". *Journal of Production Agriculture*. 10 (1997): 227–234.

[25] Lambert, D. K. “Risk Considerations in the Reduction of Nitrogen Fertilizer Use in Agricultural Production”. *Western Journal of Agricultural Economics.* 15 (1990): 234-244.

[26] Mitsch, W. J., J. W. Day Jr., J. W. Gilliam, P. M. Groffman, D. L. Hey, G. W. Randall, N. Wang. “Reducing Nitrogen Loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to Counter a Persistent Ecological Problem”. *BioScience.* 51 (2001): 373–388.

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

[28] Randall, G.W., D. R. Huggins, M. P. Russelle, D. J. Fuchs, W. W. Nelson, and J. L. Anderson. “Nitrate Losses Through Subsurface Tile Drainage in Conservation Reserve Program, Alfalfa, and Row Crop Systems”. *Journal of Environmental Quality*. 26 (1997): 1240–1247.

[29] Randall, G. W., G. L. Malzer, and B. W. Anderson. “Nitrate Losses to Tile Drainage as Affected by Nitrogen Fertilization of Corn in a Corn–Soybean Rotation”. Field Research in Soil Science. University of Minnesota. Waseca, MN. 1992.

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

[31] Randall, G.W., M. A. Schmitt. ”Advisability of Fall-Applying Nitrogen”. In *Proceedings of 1998 Wisconsin Fertilizer, Aglime, and Pest Management Conference.* University of Wisconsin, Madison, WI. 1998. 90–96.

[32] Riedall, W. E., T. E. Schumacher, S. A. Clay, M. M. Ellsbury, M. Pravecek, and P. D. Evenson. “Corn and Soil Fertility Responses to Crop Rotation with Low, Medium, or High Inputs”. *Crop Science.* 38 (1998): 427-433.

[33] Sawyer, J.E., and E.D. Nafziger. 2005. “Regional Approach to Making Nitrogen Fertilizer Rate Decisions for Corn”. *In* Proceedings of the 35th North-Central Extension Industry Soil Fertility Conference, November 16-17, 2005, Des Moines, IA. Potash & Phosphate Institute, Brookings, SD. 16-24.

[34] Sawyer, J. E. and E. D. Nafziger. “Regional Approach to Making Nitrogen Fertilizer Rate Decision for Corn”. Ames, Iowa State University. 2006. [Online] http://extension. iastate.edu/Publications/

[35] Shapiro, C.A., R.B. Ferguson, G.W. Hergert, A. Dobermann, and C.S. Wortmann. Fertilizer Suggestions for Corn. NebGuide G74-174-A. Cooperate Extension, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Lincoln, NE. 2003.

[36] Torbert, H. A., K. N. Potter, J. E. Morrison. “Tillage system, Fertilizer Nitrogen Rate, and Timing Effect on Corn Yields in the Texas Blackland Prairie”. *Agronomy Journal*. 93 (2001): 1119-1124.

[37] Uri, N. D. “Environmental Considerations in Fertilizer Use Decision”. *Environmental Geology.* 34 (1998): 103-110.

[38] U.S. Department of Agriculture. “Nitrate Occurrence in U.S. Waters (and Related Questions)”. USDA. Washington. DC. 1991.

[39] Vetsch, J.A., G.W. Randall. “Corn Production as Affected by Nitrogen Application Timing and Tillage”. *Agronomy Journal*. 96 (2004): 502-509.

[40] Weed, D.A.J., and R.S. Kanwar. “Nitrate and Water Present in and Flowing from Root-Zone Soil”. *Journal of Environmental Quality*. 25 (1996): 709–719.

[41] Yadav, S. N., W. Peterson, K. W. Easter. “Do Farmers Overuse Nitrogen Fertilizer to the Detriment of the Environment?” *Environmental and Resource Economics*. 9 (1997): 323-340.

CHAPTER 2: TIMING OF FERTILIZER APPLICATIONS: ENVIRONMENTAL IMPLICATIONS

2.1. Introduction

The literature is replete with studies focused on the timing of nitrogen application. The general conclusion among researchers is that nitrogen fertilizer should be applied nearest to the time it is needed by the crop, i.e., side-dressed several weeks after corn emergence (Huang *et al.*, 2000; Huang, Hewitt, and Shank, 1998; Fuglie and Bosch, 1995; Bosch, Cook, and Fuglie*,* 1995; Blackmer, 1995). For both agronomic and environmental reasons, spring post-emergent application of nitrogen fertilizer is frequently superior to fall and spring pre-emergent applications because less nitrogen is available for leaching, runoff, and denitrification (Huang and Uri, 1995; Huang, Hewitt, and Shank, 1998; Huang *et al*., 1998; Dinnes *et al*., 2002; Randall and Schmitt, 1998; Uri, 1998a; Blackmer, 1995). As a result, less loss of nitrogen occurs in the one to three months between application and nitrogen uptake. Still, fall nitrogen application remains a common practice used by farmers in the Midwest (Dinnes *et al*., 2002; Vetsch and Randall, 2004; Randall, Vetsch, and Huffman, 2003). There are several reasons given as to why farmers might apply nitrogen in fall: usually farmers have more time during the fall (the opportunity cost of time is lower in the fall), uncertain weather conditions in the spring may shorten the time available for fertilizer application during the growing season, increasing the risk of yield loss from inadequate nitrogen availability, potential for soil compaction following harvest is generally less, and, finally, fertilizer pricing patterns (lower in the fall than spring) tend to encourage fall fertilizer application rather than spring or growing season applications (Randall and Schmitt, 1998; Dinnes *et al*., 2002; Huang, Hewitt, and Shank, 1998).

The empirical literature addressing the timing of nitrogen fertilizer application has mainly focused on spring application and involved testing the hypothesis that excess fertilizer application at planting is used to insure against weather conditions that might not permit a later application (Feinerman, Choi, and Johnson, 1990; Huang, Hansen, and Uri, 1994; Huang, Hewitt, and Shank, 1998; Bontems and Thomas, 2000). All these studies show substantially higher fertilizer application rates whenever farmers face weather uncertainty, with the magnitude of extra fertilizer application being higher for risk-averse farmers compared to risk-neutral ones. They also found that risk aversion leads to heavier reliance on early applications.

Uncertain weather conditions result in uncertainty about available nitrogen, therefore some studies looked at the effect of nitrogen testing on fertilizer use (Fuglie and Bosch, 1995; Bosch, Cook, and Fuglie, 1995; Huang, Hewitt, and Shank, 1998; Babcock, 1992; Babcock and Blackmer, 1994; Wu and Babcock, 1998; Musser *et al.,* 1995). These studies showed that temporal uncertainty regarding nitrogen levels at the time of fertilizer application can affect the optimal nitrogen fertilizer application rate and concluded that use of soil nitrogen testing to remove the temporal uncertainty of nitrate concentration in the soil can reduce average nitrogen fertilizer application rates. The study of Wu and Babcock (1998) extended farmers' choice of nitrogen management practices to nitrogen testing, rotation, and tillage. They analyzed adoption decision of different crop management plans such as different combinations of these practices and its effects on fertilizer use and crop yields. They found that adoption of conservation tillage, rotation and nitrogen testing decreases nitrogen fertilizer rates.

There are few studies that have looked at fall fertilizer application (Huang and Uri, 1995; Huang, Hewitt, and Shank, 1998; Huang *et al.*, 2000). Huang and Uri (1995) present an analytical model for determining the optimal timing of fertilizer application in crop production. The model describes the factors that contribute to a farmer's decision on determining the optimal application timing of nitrogen fertilizer by combining ex-ante and ex-post assessments of likely weather conditions after planting. Huang, Hewitt, and Shank (1998) use the model proposed by Huang and Uri (1995) to calculate compliance costs of timing nitrogen applications. Finally, Huang *et al.* (2000) exploit the same model to propose insurance that might be used to promote adoption of growing-season only fertilizer application. The model used in all these studies considers fall and spring fertilizer applications. However, it does not account for the role that amount of fertilizer applied in fall plays on farmers' decision of whether to fertilize in spring. Failure to account for relationship between fall and spring fertilizer applications results in inconsistent parameters estimates.

The goals of this chapter are twofold. First, I seek to determine which factors influence the use of fall and early spring fertilizer applications in a modeling framework that recognizes the interrelationship between the two decisions. Second, I examine the implications of these practices on overall nitrogen use. One of the main hypotheses of the proposed model is that the decision-making for spring application depends not only on the fact that fall fertilizer application was used but also on the amount of fertilizer applied in fall. Therefore, the model includes the amount of fertilizer applied in fall as an explanatory variable for decision-making on spring fertilizer application[1]. I anticipate that a higher rate of nitrogen applied in fall will result in a lower probability of spring nitrogen application. Similarly, a higher the rate of nitrogen applied in fall should, all else equal, result in a lower rate of nitrogen applied in early spring.

2.2. The Model

A double-hurdle approach is employed for modeling individual farmer's decision making on whether to apply fertilizer at certain time and how much to apply. Advantages of using a double hurdle model for adoption models with sample selection problems are discussed by Cooper and Keim (1996) and Uri (1998b). Recent Bayesian treatments of the approach can be found in Deb, Munkin, and Trivedi (2006), Koop, Poirier, and Tobias (2007), Munkin, and Trivedi (2003). According to the logic of double-hurdle models, farmers must pass two separate hurdles in each season before they are observed to have positive fertilizer application levels. These two hurdles are the participation decision (whether to apply fertilizer during the season) and the consumption decision (how much to apply). For example, consider

---

[1] An alternative specification of the model includes F_i^* rather than Y_{Fi}^* as an explanatory variable for decision-making on spring fertilizer application, as suggested by B.A. Babcock. Farmers' decision on timing of fertilizer application is then modeled as a binary decision whether to apply fertilizer in fall or in spring.

fall fertilizer application. Following Koop, Poirier, and Tobias (2007), the participation decision of farmer *i* is assumed to be driven by a latent variable F_i^*, with

$$F_i^* = x_{1i}\beta_1 + z_{1i}\alpha_1 + \varepsilon_{1i}$$

where x_{1i} and z_{1i} are exogenous factors (such as education, land characteristics and fertilizer prices) assumed to influence the participation decision, β_1 and α_1 are parameters to be estimated, and ε_{1i} captures unobserved attributes influencing the farmer's decision. The distinction between x_{1i} and z_{1i} is that the latter variables do not enter the subsequent spring variables and, hence, serve as instrumental variables. While the latent variable is not observed, we do observe the binary outcome F_i, where:

$$F_i = \begin{cases} 1, & F_i^* > 0 \\ 0, & F_i^* \leq 0. \end{cases}$$

The fall fertilizer consumption decision is similarly driven by a latent variable Y_{Fi}^*, where

$$Y_{Fi}^* = x_{2i}\beta_2 + z_{2i}\alpha_2 + \varepsilon_{2i}.$$

However, fertilizer application levels are only observed if the farmer has passed the participation hurdle; i.e., one observes

$$Y_{Fi} = \begin{cases} Y_{Fi}^* & if\ F_i^* > 0 \\ 0 & otherwise \end{cases}$$

Turning to spring (pre-emergent) fertilizer applications, a similar double-hurdle model is considered.[2] The primary difference here is that it is assumed that the amount of fertilizer applied in the fall (i.e., Y_{Fi}) impacts both the spring participation and consumption decisions. Thus, the latent variable for the spring participation decision is given by:

$$S_i^* = x_{3i}\beta_3 + \delta_3 Y_{Fi} + \varepsilon_{3i},$$

---

[2] In this analysis, I focus primarily on pre-plant fertilizer applications (i.e., both fall and early spring) because only a small portion of the farmers in data set applied fertilizer during the growing season.

with the observed participation outcome given by:

$$S_i = \begin{cases} 1, & S_i^* > 0 \\ 0, & S_i^* \leq 0 \end{cases}$$

Similarly, the latent variable governing the spring consumption decision is given by:

$$Y_{Si}^* = x_{4i}\beta_4 + \delta_4 Y_{Fi} + \varepsilon_{4i},$$

with the observed level of spring fertilizer application given by

$$Y_{Si} = \begin{cases} Y_{Si}^* & if\ S_i^* > 0 \\ 0 & otherwise. \end{cases}$$

The error vector $\varepsilon_{\bullet i} = \left(\varepsilon_{1i}, \varepsilon_{2i}, \varepsilon_{3i}, \varepsilon_{4i}\right)'$ is assumed to be normally distributed, allowing for possible correlations among the unobservables driving the fertilizer application decisions in both seasons; i.e., $\varepsilon_{\bullet i} \sim N\left(0, \Sigma\right)$ with

$$\Sigma = \begin{pmatrix} \sigma_1^2 & \sigma_{12} & \sigma_{13} & \sigma_{14} \\ & \sigma_2^2 & \sigma_{23} & \sigma_{24} \\ & & \sigma_3^2 & \sigma_{34} \\ & & & \sigma_4^2 \end{pmatrix}.$$

These possible correlations imply that instrumental variables are required for identification of the parameters in the full model. These are labeled as z_{1i} and z_{2i} in the fall fertilizer latent variable equations.

2.3. Estimation Details

I estimate the model derived in Section 2 using a Bayesian framework, combining data augmentation and Gibbs sampling procedures. In this section, I outline the derivation of the posterior distribution and the sampling routine, relegating details of the sampler to an appendix.

2.3.1. Posterior Distribution

The full system of equations to be estimated is given by:

$$
\begin{aligned}
F_i^* &= x_{1i}\beta_1 + z_{1i}\alpha_1 + \varepsilon_{1i} \\
Y_{Fi}^* &= x_{2i}\beta_2 + z_{2i}\alpha_2 + \varepsilon_{2i} \\
S_i^* &= x_{3i}\beta_3 + \delta_3 Y_{Fi} + \varepsilon_{3i} \\
Y_{Si}^* &= x_{4i}\beta_4 + \delta_4 Y_{Fi} + \varepsilon_{4i}
\end{aligned} \qquad (2.3.1)
$$

Since F_i^* and S_i^* in the participation equations are unobservable, only the ratios $\frac{\beta_1}{\sigma_1}$, $\frac{\alpha_1}{\sigma_1}$, $\frac{\beta_3}{\sigma_3}$, and $\frac{\delta_3}{\sigma_3}$ are identified. One way to deal with identification problem is to restrict the error variances in participation equations to unity. McCulloch, Polson and Rossi (2000) provide the Bayesian analysis of the multinomial probit model, which incorporates the identification constraint by setting the one diagonal element of the covariance matrix equal to one. Nobile (2000) proposes way to generate Wishart and inverted Wishart random matrices conditional on one of the diagonal elements.

However, since (3.3) contains two participation equations, it would require imposing two constraints on the diagonal elements of the covariance matrix: $\sigma_1 = 1$ and $\sigma_3 = 1$. Therefore, I follow McCulloch and Rossi (1994) approach where a proper prior is specified for the full set of parameters (θ, Σ) and the marginal posterior of the identified parameters (β_1 / σ_1, α_1 / σ_1, β_3 / σ_3, and δ_3 / σ_3) is reported. Thus, the prior on the identified parameters is the marginal prior of (β_1 / σ_1, α_1 / σ_1, β_3 / σ_3, and δ_3 / σ_3) derived from the prior distribution specified for the full set of parameters (θ, Σ). The approach is taken because of the difficulties associated with a Bayesian analysis of covariance matrices with constraints.

The four equations for each individual are stacked in the following manner:

$$\tilde{y}_i^* = \begin{pmatrix} F_i^* \\ Y_{Fi}^* \\ S_i^* \\ Y_{Si}^* \end{pmatrix}_{4\times 1} , \quad \tilde{y}_i = \begin{pmatrix} F_i \\ Y_{Fi} \\ S_i \\ Y_{Si} \end{pmatrix}_{4\times 1} , \quad \varepsilon_i = \begin{pmatrix} \varepsilon_{1i} \\ \varepsilon_{2i} \\ \varepsilon_{3i} \\ \varepsilon_{4i} \end{pmatrix}_{4\times 1}$$

$$X_i = \begin{pmatrix} x_{1i} & z_{1i} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & x_{2i} & z_{2i} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & x_{3i} & Y_{Fi} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & x_{4i} & Y_{Fi} \end{pmatrix}_{4\times k} \text{, and} \qquad \theta = \begin{pmatrix} \beta_1 \\ \alpha_1 \\ \beta_2 \\ \alpha_2 \\ \beta_3 \\ \delta_3 \\ \beta_4 \\ \delta_4 \end{pmatrix}_{k\times 1}$$

where k is the total number of explanatory variables in all four equations. The system can be expressed then as

$$\begin{aligned} &\tilde{y}_i^* = X_i\theta + \varepsilon_i \\ &\varepsilon_i \sim N(0, \Sigma). \end{aligned}$$

Finally, stacking over individuals yields:

$$\tilde{y}^* = X\theta + \varepsilon \quad \sim N(X\theta, I_n \otimes \Sigma)$$

where

$$\tilde{y}^* = \begin{pmatrix} \tilde{y}_1^* \\ \tilde{y}_2^* \\ \vdots \\ \tilde{y}_n^* \end{pmatrix}_{4n\times 1} , \quad \tilde{y} = \begin{pmatrix} \tilde{y}_1 \\ \tilde{y}_2 \\ \vdots \\ \tilde{y}_n \end{pmatrix}_{4n\times 1} , \quad X = \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{pmatrix}_{4n\times k} , \varepsilon = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix}_{4n\times 1}$$

For computational simplicity, I use a data augmentation approach (Tanner and Wong, 1987; Albert and Chib, 1993), treating the latent data $\tilde{y}^*$ as additional parameters of the model and, thus, making them a part of the posterior. Using Bayes Theorem, the augmented posterior is given by

$$\begin{aligned}
p\left(\tilde{y}^*,\theta,\Sigma\middle|\tilde{y}\right) &\propto p\left(\tilde{y}\middle|\tilde{y}^*,\theta,\Sigma\right)p\left(\tilde{y}^*\middle|\theta,\Sigma\right)p(\theta,\Sigma)\\
&\propto p(\theta,\Sigma)\prod_{i=1}^{n}p\left(\tilde{y}_i\middle|\tilde{y}_i^*\right)p\left(\tilde{y}_i^*\middle|\theta,\Sigma\right)\\
&\propto p(\theta,\Sigma)\prod_{i=1}^{n}\Big\{\left[I(F_i=1)I\left(F_i^*>0\right)+I(F_i=0)I\left(F_i^*\le 0\right)\right]\times\\
&\qquad\left[F_i\times I\left(Y_{Fi}=Y_{Fi}^*\right)+(1-F_i)I(Y_{Fi}=0)\right]\times\\
&\qquad\left[I(S_i=1)I\left(S_i^*>0\right)+I(S_i=0)I\left(S_i^*\le 0\right)\right]\times\\
&\qquad\left[S_i\times I\left(Y_{Si}=Y_{Si}^*\right)+(1-S_i)I(Y_{Si}=0)\right]\Big\}\,p\left(\tilde{y}^*\middle|\theta,\Sigma\right),
\end{aligned}$$

where the second line follows from the assumed independence across individuals and I denotes an indicator function taking on the value one if the statement in the parenthesis is true, and is zero otherwise. Conditional on the parameters of the model, the augmented likelihood can be expressed as

$$\begin{aligned}
p\left(\tilde{y}^*\middle|\theta,\Sigma\right) &= (2\pi)^{-\frac{4n}{2}}\left|I_n\otimes\Sigma\right|^{-\frac{1}{2}}\exp\left(-\frac{1}{2}\left(\tilde{y}^*-X\theta\right)'\left(I_n\otimes\Sigma\right)^{-1}\left(\tilde{y}^*-X\theta\right)\right)\\
&\propto\left(\left|I_n\right|^4\left|\Sigma^n\right|\right)^{-\frac{1}{2}}\exp\left(-\frac{1}{2}\left(\tilde{y}^*-X\theta\right)'\left(I_n\otimes\Sigma\right)^{-1}\left(\tilde{y}^*-X\beta\right)\theta\right)\\
&\propto\left|\Sigma\right|^{-\frac{n}{2}}\exp\left(-\frac{1}{2}\sum_{i=1}^{n}e_i'\Sigma^{-1}e_i\right)\\
&\propto\left|\Sigma\right|^{-\frac{n}{2}}\exp\left(-\frac{1}{2}\sum_{i=1}^{n}\left(\tilde{y}_i^*-X_i\theta\right)'\Sigma^{-1}\left(\tilde{y}_i^*-X_i\theta\right)\right).
\end{aligned}$$

I choose an independent Normal prior distribution on θ:

$$\theta\sim N\left(\mu_{\theta_0},V_{\theta_0}\right),$$

where μ_{θ_0} and V_{θ_0} denote the prior mean and covariance matrix of θ.

Finally, I employ an Inverse Wishart prior distribution for the covariance matrix Σ, with

$$\Sigma^{-1}\sim W\left(a^{-1},b\right),$$

where a is a positive definite matrix of size 4×4, and b is a scalar.

2.3.2. Posterior Simulation

The conditional posteriors of both θ and Σ are proportional to the product of the likelihood and the respective prior distribution. As shown in Appendix A, the conditional posterior for θ is Normal:

$$p\left(\theta \middle| y^*, \Sigma\right) = N\left(\mu_{\theta_1}, V_{\theta_1}\right)$$

where

$$\begin{aligned} V_{\theta_1} &= \left(\sum_{i=1}^{n} X_i' \Sigma^{-1} X_i + V_{\theta_0}^{-1} \right)^{-1} \\ \mu_{\theta_1} &= V_{\theta_1} \left(\sum_{i=1}^{n} X_i' \Sigma^{-1} y_i^* + V_{\theta_0}^{-1} \mu_{\theta_0} \right), \end{aligned} \tag{2.3.2}$$

and the conditional posterior distribution of Σ is Inverse Wishart:

$$\Sigma^{-1} \middle| \tilde{y}_i^*, \theta \sim W\left(\left(\sum_{i=1}^{n} \left(\tilde{y}_i^* - X_i\theta \right)' \left(\tilde{y}_i^* - X_i\theta \right) + a \right)^{-1}, n+b \right). \tag{2.3.3}$$

Finally, the data augmentation step draws the values of latent variables F_i^*, Y_{Fi}^*, S_i^*, and Y_{Si}^* conditional on the observed data $\tilde{y}_i$ and parameters of the model θ and Σ. The conditional posterior distributions of latent variables F_i^* and S_i^* are truncated normal:

$$\begin{aligned} F_i^* \middle| \beta, \Sigma, \tilde{y}_i &\sim TN_{R\left(F_i^*\right)}\left(\mu_{F^*}, \sigma_{F^*}^2 \right) \\ S_i^* \middle| \beta, \Sigma, \tilde{y}_i &\sim TN_{R\left(S_i^*\right)}\left(\mu_{S^*}, \sigma_{S^*}^2 \right), \end{aligned}$$

where $TN_R^*\left(\mu, \sigma^2\right)$ denotes normal distribution with mean μ and variance σ^2 truncated to the region R. For each individual i these distributions are truncated to the regions:

$$R\left(F_i^*\right) = \begin{cases} \left[0, \infty\right) & if\ F_i = 1 \\ \left(-\infty, 0\right) & if\ F_i = 0 \end{cases}$$

and $$R\left(S_i^*\right) = \begin{cases} \left[0, \infty\right) & if\ S_i = 1 \\ \left(-\infty, 0\right) & if\ S_i = 0 \end{cases}$$

I follow Geweke (1991) to draw values from these truncated normal distributions. Each latent index is sampled from a univariate truncated normal density conditional on the current values of other latent indices using the inverse distribution function method.

The latent variables Y_{Fi}^* and Y_{Si}^* are drawn only for those observations for which $F_i = 0$ and $S_i = 0$, respectively. Specifically, they are drawn from the normal distributions:

$$Y_{Fi}^* \big| \beta, \Sigma, \tilde{y}_i \sim N\left(\mu_{YF^*}, \sigma_{YF^*}^2\right)$$

$$Y_{Si}^* \big| \beta, \Sigma, \tilde{y}_i \sim N\left(\mu_{YS^*}, \sigma_{YS^*}^2\right).$$

Again, I sample each latent index from a univariate normal density conditional on the current values of other latent indices using the inverse distribution function method. In those cases in which $F_i = 1$ or $S_i = 1$, then $Y_{Fi}^* = Y_{Fi}$ and $Y_{Si}^* = Y_{Si}$, respectively.[3]

2.4. Data

The data used in this paper comes from the Agricultural Resource Management Survey (ARMS) data survey for the year 2001, conducted by the Economic Research Service (ERS) and the National Agricultural Statistics Service (NASS) of the U.S. Department of Agriculture (USDA). This survey provides field-level information on the financial condition, production practices, resource use, and the economic well-being of U.S. farm households. The data used in our analysis comes from two phases in the data collection process, phases II and III.

Phase II of the ARMS survey collects data associated with agricultural production practices, resource use, and variable costs of production for specific commodities and is conducted from September through December of the survey year. Phase III collects whole-farm finance variables, operator characteristics, and farm household information and is conducted from February through April, with the reference period being the previous year. Respondents sampled in Phase II are asked to

---

[3] Generated data experiment was performed first to check the validity of the calculation code.

complete a Phase III report. Data from both phases provide the link between agricultural resource use and farm financial conditions.

Farm operators included in the ARMS data are selected to ensure adequate coverage by state and region and to minimize reporting burden. Strata are based on state, the value of agricultural sales (farm size), and type of farm. NASS provides survey weights that account for these design features as well as for additional information available at the population level. Because of the complex design of the survey, all official estimates from the survey should be properly weighted. Therefore, NASS recommends the design-weighted approach as appropriate for many of the analyses for users of ARMS data (Panel to Review USDA's Agricultural Resource Management Survey, National Research Council, 2007). Ignoring the survey design can result in bias estimates, and make it impossible to perform statistically valid inferences. However, including variables related to the design of the survey as predictor variables in a model results in a new, conditional model, for which the design is ignorable. In that case, model-based inference yields the appropriate conclusions for the sample, but not necessarily for the unweighted population. Therefore, to account for the survey design of the ARMS data, I included stratums in the set of explanatory variables. Particularly, state and farm size are included as predictive variables in the model.

ARMS data on corn production for 2001 includes data for 19 states. However, only four main corn producing states were chosen for analysis in the current chapter: Illinois, Indiana, Iowa, and Ohio. Approximately 50% of all corn grown in the U.S. is from these four states. The resulting data set contains a total of 1726 observations.

2.4.1. Definitions of Variables

The definitions of variables used in estimation, as well as an indication as to which season's equation they were used for, are given in Table 2.1. Mean values and standard deviations of all variables are given in Table 2.2. The dependent variables used in the estimating equations include dummy variables reflecting farmer's participation decision on fall fertilizer application (i.e., $F_i = 1$ if fall application was used and = 0 otherwise), early spring fertilizer application (i.e., $S_i = 1$ if early spring application was used and = 0 otherwise), and the nitrogen fertilizer application rates in fall and early spring measured in pounds per acre. As can be seen from the Table 2.2, about 18% of the sample applied fertilizer in the fall and 72% applied in the spring. Not reported is the fact that 13% of the sample applied fertilizer in both spring and fall.

The independent variables consist of farm and operator characteristics, cropping history, and soil quality determinants. The set of variables governing the farmer's decision regarding fall fertilizer application is the same as the set used to explain the amount of nitrogen fertilizer applied in fall. Similarly, the set of variables governing the farmer's participation decision regarding early spring fertilizer application is the same as those allowed to impact the amount of nitrogen fertilizer applied in early spring.

An operator characteristic included is formal schooling. I hypothesize that more educated farmers are likely to be more aware of the negative environmental consequences of fall fertilizer application, so they are more likely to apply nitrogen in the spring rather than in the fall. The discrete education variable takes value of "1" if the farm operator had some college education and "0" otherwise. Total acreage operated by the farmer was included as an indicator of size of operation.

The amount of fertilizer applied is typically determined after "credit" is given for the amount of nutrients available from the soil, the previous legume crop, and livestock manure applied. Once the needed amount of fertilizer is estimated, management decisions can be made about the fertilizer application method and timing. Therefore, dummy variables for whether the field received manure and whether corn was rotated with a legume crop are included in the model. Giving appropriate nitrogen credits to animal manure applications is recommended to avoid overapplication of nitrogen fertilizer. Therefore, farmers who apply manure and rotate corn with a legume crop are expected to reduce the amount of nitrogen applied and have lower probability of fall fertilizer application.

To capture the yield differences among fields and farms, the variable “Land Capability Class” was used. The Land Capability Classification indicates the suitability of soils for most kinds of field crops. Land is evaluated on the basis of the range of potential crops, productivity, ease of management and risk of degradation. Capability classes are designated by the numbers 1 through 8. The numbers indicate progressively greater limitations and narrower choices for agricultural production. A dummy variable was created that takes the value of one if the capability class is 1 or 2, and is zero otherwise. I expect farmers to use more of nitrogen on the land with higher productivity as marginal return on nitrogen will be higher.

As noted above, for identification purposes, it is necessary to include instrumental variables (denoted by z_{1i} and z_{2i}) into the fall participation and consumption latent variables (i.e., F_i^* and Y_{Fi}^*, respectively). The opportunity cost of labor is significantly higher during the late spring and growing season than during the fall (Huang, Hewitt, and Shank, 1998; Randall and Schmitt, 1998; Dinnes *et al*., 2002). Therefore, the off-farm employment of the farmer can be used as an instrumental variable specific to fall fertilizer application. The variable OFF-FARM represents the number of days worked off farm. Working off-farm leaves less time for a farmer to work in the field, particularly during pre-planting and the planting season when a lot of work needs to be done in a short period of time. Working off-farm therefore increases a farmer’s risk of not being able to finish everything on time and increases the opportunity cost of time for a farmer during the planting season. As a result, a farmer who works off-farm is hypothesized to apply fertilizer in the fall. Thus, I expect a positive sign for off-farm employment parameter in the fall fertilizer application equation.

The number of days available to complete the application of fertilizer is also an important consideration in deciding on the timing of fertilizer application (Iowa State University Extension, 2007a; Rotz and Harrigan, 2004; Dillon, 1999). States report the number of days each week that soil and moisture conditions are suitable for fieldwork. This data also captures climatic and weather differences among sites that affect farmers’ decision making regarding the timing of fertilizer application (Fletcher and Featherstone, 1987; Feinerman, Choi, and Johnson, 1990; Kurkalova, Kling, and Zhao, 2006; Wu *et al.*, 2004). Estimates of the number of suitable fieldwork days are based on weekly records. The spring data covers the usual corn planting dates of mid-April to mid-May. The fall data covers the period of mid-September to the end of October. The values represent the median number of days reported each week and provide a second instrument for use in the fall fertilizer decision equations. Finally, to capture the differences across the states that are not reflected by the independent variables, state dummies are introduced into each equation of the model.

2.5. Results

For each of the specifications, 25,000 draws from the posterior distribution were obtained. The first 5,000 were discarded as a burn-in, and the remaining 20,000 were used for analysis[4]. Posterior means, standard deviations, and probabilities of being positive for each of the parameters of interest are given in Table 3a and 3b, covering the fall and spring application decisions, respectively.

Several important results emerge from Tables 2.3a and 2.3b. First, the posterior means and standard deviations on the off-farm employment variable in Table 2.3a suggest that the opportunity cost of farmers' time in spring plays a significant role in their decision-making regarding the timing of fertilizer application. Working off –farm leaves farmers with fewer days for field work during the planting season so farmers who work off-farm have a higher probability of fall fertilizer application than those who are not employed off- farm. Second, the amount of fertilizer applied in the fall was found to be crucial in the decision making process concerning spring nitrogen application, impacting both the decision as to whether to apply nitrogen in spring and the amount of spring application. This indicated in Table 2.3b by the largely negative posterior distribution (i.e., small values for $\Pr\left(\cdot > 0 \mid y\right)$) for the parameters associated with fall nitrogen application in both of the spring fertilizer equations. It appears that, all else equal, farmers who apply higher rates of nitrogen in the fall have a

---

[4] The model diagnostics was utilized to inspect the performance of the posterior simulators. First, plots of lagged autocorrelations were examined to check how quickly chain mixes. Second, posterior simulators for different starting values were plotted. Figure 2.7 presents results of model diagnostics on only for a subset of parameters.

lower probability of applying nitrogen in the spring. On average, for every pound of additional fertilizer applied in the fall, about 2.5 pounds less fertilizer is applied in early spring.

Other variables included in the model also generally perform as expected. The manure and rotation variables affect both whether and how much nitrogen is applied in both seasons. Specifically, manure application and rotating corn with a legume crop tend to decrease the probability of fall application and reduce the amount of nitrogen applied. The manure coefficient is negative (with $\Pr\left(\cdot > 0 \mid y\right)$ = 0.15) suggesting that farmers applying manure apply less fertilizer. Rotating corn with a legume crop is also found to reduce the total nitrogen applied, a result that is consistent with Wu and Babcock (1998). Similar impacts arise for the spring fertilizer equations in Table 2.3b.

Field acreage and fieldwork days are also found to affect farmers' decisions regarding nitrogen application. Larger farms, requiring more time to finish planting and fertilizer application in the spring, are more likely to employ fall fertilizer and reduce their spring fertilizer application levels. Additional work days during the fall are found to increase the probability of fall fertilizer applications and the amount of fertilizer applied. Similar impacts arise during the spring season.

The performance of soil characteristics is generally consistent with agronomic information and expectations. Lands with a high land capability are found to increasingly rely upon fertilizer in both the spring and fall seasons. This result supports the importance of land quality in the choice of farming practice (Lichtenberg, 2004; Caswell and Zilberman, 1985).

2.6. Environmental Implications

In this section, I consider the implications of the estimated model, both in terms of the appropriate credits for rotation and manure use and in terms of the potential impacts of policies to reduce the nitrogen use.

2.6.1. Rotation and manure credits

The agronomic fertilizer recommendations indicate that nitrogen application rates should be adjusted to account for nitrogen supplied by previous legume crops and manure application (USDA, ERS, 2001).

When managed correctly, nutrients from previous legume crops and in livestock manure can be a valuable resource of nitrogen, therefore, crediting for rotation and manure nutrients can be an important factor in deciding nitrogen application rates (Blackmer, 2000; Sharpley *et al*., 1998). To examine this issue, the estimation results are used in this subsection to compute the amount of rotation and manure credits by farmers in different seasons: fall and early spring.

2.6.1.1. Calculation Details

The rotation nitrogen credit refers to the difference between the amount of nitrogen applied for continuous corn and nitrogen applied for corn following soybean all else equal. Likewise, the manure nitrogen credit refers to the difference between the amount of nitrogen applied without manure application and nitrogen applied with manure application.

The estimated model is used to estimate the distributions of the implied credits being used for rotation and applied manure. Specifically, the rotation credit is given by $\Delta_i^r = Y_{1i}^r - Y_{0i}^r$, where Y_{1i}^r corresponds to the amount of nitrogen applied for a corn-corn rotation for observation i and Y_{0i}^r corresponds to the amount of nitrogen applied for corn-soybean rotation. Similarly, the manure credit is given by $\Delta_i^m = Y_{1i}^m - Y_{0i}^m$, where Y_{1i}^m corresponds to amount of nitrogen applied with manure not applied and Y_{0i}^m corresponds to amount of nitrogen applied with manure applied. Credit distributions then are analyzed to check whether the timing of fertilizer application affects rotation and manure credits and if there is a significant difference between Δ_{fall}^r and Δ_{spring}^r, and between Δ_{fall}^m and Δ_{spring}^m.

The literature on the treatment effect focuses primarily on methods for estimating various average returns to the receipt of treatment. Particularly, it focuses on: (1) the average treatment effect (ATE), and (2) the effect of treatment on treated (TT) (Li, Poirier, and Tobias, 2004; Tobias, 2006).

For the current research, ATE is defined as the expected nitrogen credit for rotation and manure by a randomly chosen farmer.

A conceptually different parameter is the credit by farmers who actually used fall or spring fertilizer applications. In this case Δ represents the average credit for rotation and manure by farmers who actually used fall (spring) fertilizer application and is referred to in the literature as the Treatment on the Treated (TT).

Given notation and assuming that covariates x_i are known, I characterize the following out-of-sample sampling distributions, given θ and x_i, as follows:

(2.6.1) $p\left(\Delta \middle| \theta, x_i\right)$

(2.6.2) $p\left(\Delta \middle| \theta, x_i, F_i = 1\right)$.

The first density in (2.6.1) gives the distribution of nitrogen credit for rotation and manure by the farmer selected at random, whereas the density in (2.6.2) gives the nitrogen credit for those farmers who actually used fall (spring) fertilizer application.

Expressions (2.6.1) and (2.6.2) for ATE and TT predictive distributions are all conditioned on the parameters θ. A proper Bayesian approach to characterize the posterior predictive distributions of the nitrogen credit is to integrate out the parameters θ from the densities (2.6.1) and (2.6.2) by averaging them over the posterior distribution of those parameters. Formally,

$$(ATE): \quad p\left(\Delta \middle| x_i, Data\right) = \int_\theta p\left(\Delta \middle| \theta, x_i, Data\right) p\left(\theta \middle| Data\right) d\theta$$

$$(TT): \quad p\left(\Delta \middle| x_i, F_i = 1, Data\right) = \int_\theta p\left(\Delta \middle| x_i, \theta, F_i = 1, Data\right) p\left(\theta \middle| Data\right) d\theta,$$

where *TT* is shown for those farmers who applied fertilizer in fall with similar predictives for those farmers who applied it in early spring.

To calculate these predictives I use the following approximations (Poirier and Tobias, 2003; Tobias, 2006):

$$(ATE): \quad \hat{p}\left(\Delta \middle| x_i, Data\right) = \frac{1}{K}\sum_{k=1}^{K} p\left(\Delta \middle| x_i, \theta = \theta^k, Data\right),$$

and $$(TT): \quad \hat{p}\left(\Delta \middle| x_i, F_i = 1, Data\right) = \frac{1}{K}\sum_{k=1}^{K} p\left(\Delta \middle| x_i, \theta = \theta^k, F_i = 1, Data\right),$$

where θ^k denotes draws from the posterior distribution of θ and K denotes number of such parameter draws.

2.6.1.2. Results

There are several guides provided by University Extension illustrating how to estimate the crop available nutrients from previous legume crops and manure application (University of Nebraska-Lincoln Extension, 2006; Iowa State University Extension, 2003, 2007b). According to these guides, the nitrogen credit given for soybeans should be 40-50 lb/acre. The amount of the total nitrogen available from manure depends on the species and whether the manure is liquid or solid. The recommended manure credits for average manure application rates in Illinois, Indiana, Iowa, and Ohio in year 2001 were 110-130 lb/acre.

Two types of distributions for manure and rotation credits were constructed: (1) the farmer's expected credits in fall and spring independently on his/her timing of fertilizer application (ATE) and (2) credits by farmer who actually used fall or spring fertilizer application (TT). Specifically, Figures 2.1 and 2.2 present the ATE and TT posterior predictive distributions of rotation credits for spring applied nitrogen. From Figure 1, ATE predictive is centered near 26 (specifically, its posterior mean is 26.43), indicating that on average all farmers (independently on their timing of fertilizer application) apply 26 lb/acre more of nitrogen for continuous corn than for corn following soybean. The TT predictive in Figure 2.2 is shifted to the right compared to ATE distribution and, consequently, has higher mean and median values. Specifically, the posterior mean of TT is approximately 31 lb/acre, suggesting that on average farmers who applied fertilizer in spring used 31 lb/acre more of nitrogen for continuous corn than for corn following soybean.

Next, for the purpose of comparing rotation credits by farmers in fall and early spring, both TT posterior predictives for fall and spring are used. Specifically, Figure 2.3 presents two TT posterior predictives for rotation credit in fall and spring. As can be seen from Figure 2.3, rotation credits in spring are higher than in the fall. The posterior mean of TT for rotation credit calculated for ARMS 2001 data is 31.23 lb/acre in spring as opposed to 25.37 lb/acre for fall. Both of these values are lower than the level of rotation credit that farmers are recommended to use by Extension: 40-50 lb/acre. However, these values also suggest that applying nitrogen in spring increases the level of rotation credit relative to the fall nitrogen application.

Figure 2.1. Rotation Credit for Spring Application ATE

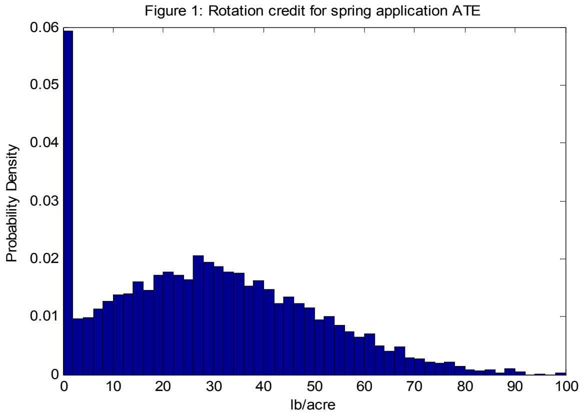


Figure 2.2. Rotation Credit for Spring Application TT

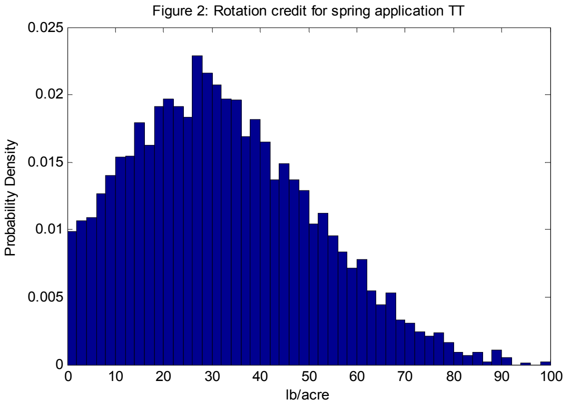
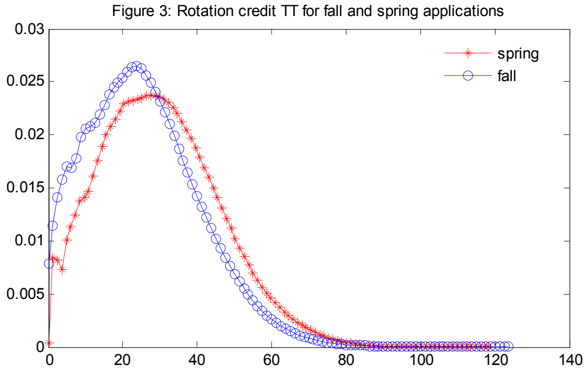


Figure 2.3. Rotation Credit for Fall and Spring Applications.



Previous attempts to quantify the soybean nitrogen credit showed that it varied with year and soil characteristics. Gentry *et al.* (2001) obtained the value of 27 kg/ha $\left(\approx 30.3\ lb/acre\right)$ of nitrogen credit in Illinois. In the research of Bundy, Andraski, and Wolkowski (1993) estimated nitrogen credits that differed significantly among locations and years and ranged from 22 to 210 kg/ha $\left(\approx 24.7\text{-}317.7\ lb/acre\right)$. The findings here are broadly consistent with the previous results.

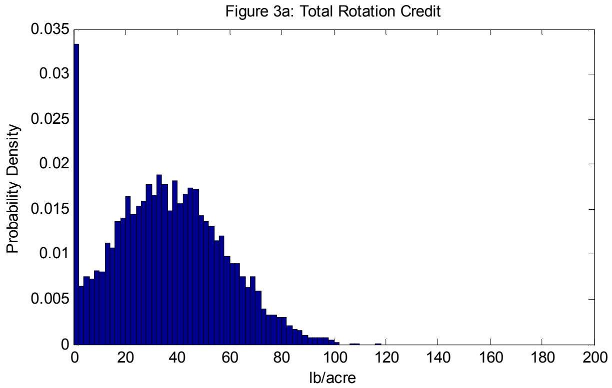
The posterior probability that on average farmers who apply fertilizer in spring credit at least 50 lb/acre of nitrogen for rotation is also calculated:

$$\Pr\left(\Delta > 50 \middle| x = \bar{x}, S_i = 1, Data\right) = 0.24 .$$

This result says that on average 76 percent of farmers do not follow recommendations and credit less than 50 lb/acre of nitrogen for rotation.

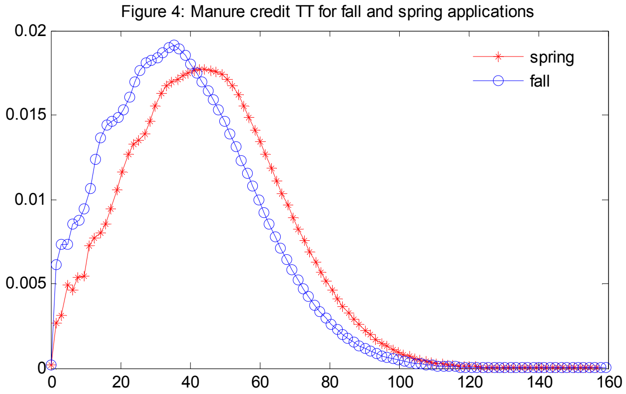
Next, the posterior predictive distribution was constructed for the “total” rotation credit. The “total” rotation credit is referred to the sum of rotation credit in fall and spring Δ^r_{fall} and Δ^r_{spring}. Specifically, Figure 2.3a presents the posterior predictive distribution of rotation credits for total applied nitrogen. From Figure 2.3a, predictive is centered near 36 indicating that on average all farmers in total apply 38 lb/acre more of nitrogen for continuous corn than for corn following soybean.

Figure 2.3a. Total Rotation Credit



Analogous results are obtained for manure credits. Figure 2.4 presents TT posterior predictives for manure credit in fall and spring. The posterior mean of TT for manure nitrogen credit calculated for ARMS 2001 data is 48.74 lb/acre for spring fertilizer application. This result indicates that on average farmers who apply fertilizer in spring use 48.74 lb/acre less of nitrogen when they apply manure than without manure application. The posterior mean of TT for manure nitrogen credit calculated for fall is 39.64 lb/acre. Again, both estimated TT values for fall and spring are lower than the level of manure credit that is recommended to farmers by Extension: 110-130 lb/acre; and the posterior mean of TT for manure credit calculated for ARMS data for spring is higher than in fall.

Figure 2.4. Manure Credit TT for Fall and Spring Applications



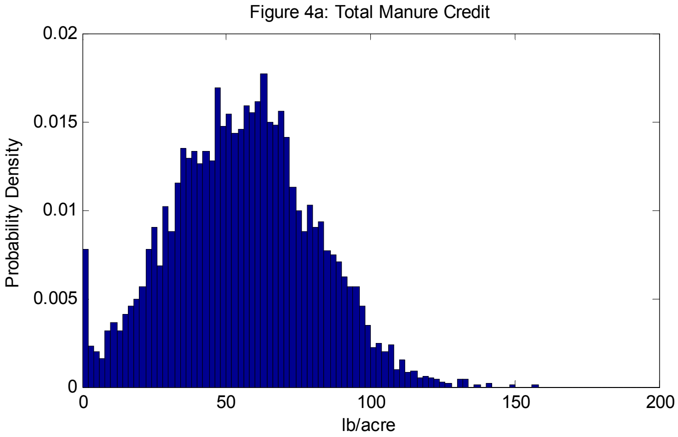
University of Minnesota Extension (2008) calculated that, on average, manure nitrogen would be approximately 75 pounds per manured corn acre for typical small dairies farm in southeastern Minnesota. The findings here are consistent with their estimates.

The posterior probability that on average farmers who apply fertilizer in spring credit at least 100 lb/acre of nitrogen for manure application is also calculated.

This result says that on average 92 percent of farmers do not follow recommendations and credit less than 100 lb/acre of nitrogen for manure application.

Next, the posterior predictive distribution was constructed for the "total" manure credit. The "total" rotation credit is referred to the sum of manure credits in fall and spring Δ^{m}_{fall} and Δ^{m}_{spring}. Specifically, Figure 2.4a presents the posterior predictive distribution of manure credit for total applied nitrogen. From Figure 2.4a, predictive is centered near 53 indicating that on average all farmers in total apply 38 lb/acre more of nitrogen without manure than with manure application.

Figure 2.4a. Total Manure Credit



Results for both rotation and manure credits suggest that applying nitrogen in spring increases the level of credit. Therefore, a policy that would induce farmers to switch from fall to spring fertilizer application might be expected to reduce the amount of fertilizer applied since farmers credit more nitrogen for rotating corn with legume crop and manure application.

2.6.2. Demand for Nitrogen Fertilizer

One way of reducing nitrogen application in corn production is imposing tax on the nitrogen. This chapter examines the potential implications of adopting a tax strategy as the policy choice to reduce the level of nitrogen application. There are several studies that focused primarily on estimating the fertilizer demand and corresponding fertilizer price elasticities (Griliches, 1958 and 1959; Roberts and Heady, 1982; Roberts, 1986; Vroomen and Larson, 1991; Denbaly and Vroomen, 1993). Some other studies investigated the effect of agro-environmental policies on agricultural production and fertilizer input demand (Onianwa *et al*., 1992; Abler and Shortle, 1995, Hertel and Stiegert, 2000; Hertel, Stiegert, and Vroomen, 1996).

Vroomen and Larson (1991) obtained estimates of -0.23 and -0.02 as the minimum own-price elasticities of demand for nitrogen and phosphorous in the Corn Belt area, and estimates of -0.85 and -1.27 as the maximum own-price elasticities of demand for both nutrients, respectively. Similarly, in their study of nutrient plant elasticities of demand for corn production in the United States, Denbaly and Vroomen (1993) obtained estimates of -0.23, -0.02, and -0.16 as the short-run elasticities of demand for nitrogen, phosphorous, and potassium in corn production, and -0.48, -0.30, and -0.27 for the long-run price elasticities of demand for these plant nutrients, respectively. Onianwa, Alderfer, and Levins (1992) estimated the elasticity of demand for nitrogen in corn production in Minnesota to be -0.35. Hertel, Stiegert, and Vroomen (1996) obtained the estimate of -0.22 for own-price elasticity of demand for nitrogen in corn production in Indiana.

The calculation of the elasticity of demand for sample selection models is different from linear models (Yen, 2005). If the probability of a positive observation for each dependent variable y_i is $P\left(y_i > 0\right) = \Phi\left(z'\alpha_i\right)$ with the observed $y_i = x'\beta_i$, and $y_i = 0$ otherwise, then the elasticity of the unconditional mean with respect to x_j is

$$e_i^u = \left\{ \frac{\beta_{ij}}{x'\beta_{ij}} + \lambda\left(z'\alpha_i + \rho_{ii}^{vu}\sigma_i\right)\alpha_{ij} \right\} x_j \text{ where } \lambda = \frac{\phi(\cdot)}{\Phi(\cdot)},$$

and the elasticity of the conditional mean with respect to x_j is

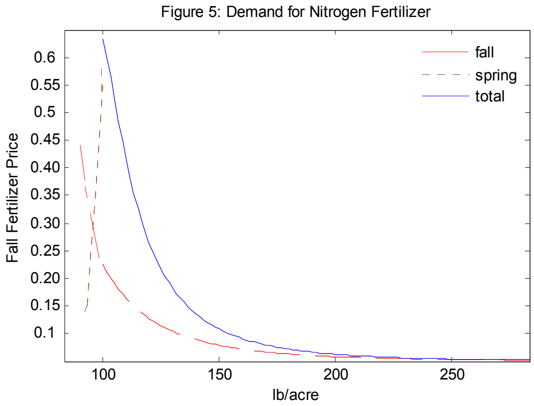
$$e_i^c = \left\{ \frac{\beta_{ij}}{x'\beta_{ij}} + \left[\lambda\left(z'\alpha_i + \rho_{ii}^{vu}\sigma_i\right) - \lambda\left(z'\alpha_i\right)\right]\alpha_{ij} \right\} x_j .$$

Then, the elasticity of the conditional mean of demand for fall applied nitrogen by the average farmer from the ARMS 2001 data is calculated to be $e^c = -0.63$ with standard error of 0.22. Corresponding probability of elasticity value being positive $\Pr\left(\cdot > 0 \mid y\right)$=0.15.

One of the main assumptions of this model is that the amount of nitrogen applied in the fall affects the probability of spring nitrogen application and the amount of nitrogen applied in spring as well. Therefore, the effect of the price of fall nitrogen on demand for nitrogen in spring is also calculated to see the substitution effect between nitrogen applied in fall and spring. Then, the total demand for nitrogen in both periods is calculated.

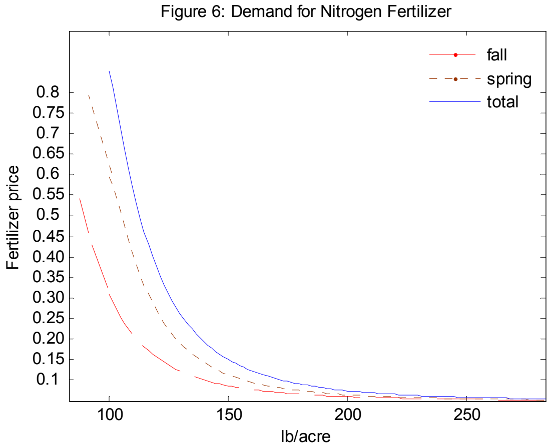
There are two scenarios to investigate how demand for nitrogen fertilizer is affected by the price of nitrogen. The first scenario looks at how the change in the price for fall applied nitrogen affects the quantity of nitrogen demanded in the fall, in the spring, and in total. Keeping the price of nitrogen in spring constant, the quantity of fertilizer applied in fall and amount of fertilizer applied in spring are calculated for different prices of fall applied nitrogen. Figure 2.5 shows the demand for nitrogen in fall, demand for nitrogen in spring, and the total demand for nitrogen in both periods. As expected, the higher the price of fall applied nitrogen, the less of nitrogen fertilizer is demanded. Moreover, due to substitution effects, the higher price of nitrogen in the fall makes farmers apply more nitrogen in the spring. As a result, the total demand for nitrogen in both periods is more inelastic relative to the demand for fall nitrogen, and is calculated to be $e^c = -0.39$.

Figure 2.5. Demand for Nitrogen Fertilizer



The second scenario examines how the changes in both prices for fall and spring applied nitrogen affect the demand for nitrogen in each period and total demand for nitrogen fertilizer. In this scenario both prices for fall applied nitrogen and spring applied nitrogen change simultaneously and the amount of nitrogen applied in both periods is calculated. Figure 2.6 presents quantities of nitrogen demanded in fall, in spring, and the total demand for nitrogen in both periods. As expected, the higher the price of nitrogen, the less is the quantity of nitrogen applied. Moreover, the total demand for nitrogen becomes more inelastic and is calculated to be $e^c = -0.26$.

Figure 2.6. Demand for Nitrogen Fertilizer



In both scenarios the total demand for nitrogen fertilizer was found to be quite inelastic, with estimated elasticities equal to -0.39 and -0.26, respectively. These results suggest that the 10 percent tax imposed on fall nitrogen will reduce the total amount of nitrogen applied by 3.9 percent, and a 10 percent tax on nitrogen fertilizer (fall and spring) will result in 2.6 percent reduction in the total amount of nitrogen demanded. These results support previous findings by Vroomen and Larson (1991), Denbaly and Vroomen (1993), Onianwa *et al*. (1992), Hertel, Stiegert, and Vroomen (2000) who obtained low estimates for own-price elasticity of demand for nitrogen in corn production.

Control of nonpoint source pollution often requires regulation of inputs. Wu and Tanaka (2005) found that a fertilizer-tax is much more cost effective than other easement policies (incentive payments for conservation tillage, for corn-soybeans rotations, and for cropland retirement) and advocated its use for reducing nitrogen loads from Upper Mississippi River Basin to the Gulf of Mexico. Estimated elasticities in this chapter indicate that a tax on nitrogen fertilizer would reduce nitrogen fertilizer use in corn production. However, the effectiveness of a tax in reducing nitrogen fertilizer use is limited due to elasticity being less than one.

2.7. Conclusions

Spring fertilizer application can reduce the amount of nitrogen leaving a field via leaching, runoff, and denitrification. All this makes spring nitrogen application more desirable from an environmental point of view. This chapter proposes a model to estimate the financial incentives for switching from fall to spring nitrogen application. The model accounts for the effect that fall fertilizer application has on spring fertilizer application. As expected, the results show that a higher rate of nitrogen applied in fall lowers probability of spring nitrogen application. Moreover, a higher rate of nitrogen applied in the fall yields a lower rate of nitrogen applied in early spring.

Agronomists have long recommended that, nitrogen application rates should be adjusted to account for nitrogen supplied by previous legume crops and manure. If farmers do not credit other sources of nitrogen, they may apply more nitrogen than can be used by crops and increase the amount of nitrogen leaving the field. Results of this research show that, on average, farmers credit less nitrogen available from manure and previous legume crops than is recommended by University Extension.

Furthermore, those farmers who apply fertilizer in the fall credit less nitrogen from rotation and manure than those farmers who apply fertilizer in spring.

Calculated own-price elasticities of the total demand for nitrogen are equal to -0.39 and -0.26 and suggest that imposing tax on the nitrogen fertilizer works as a tool for reducing the amount of fertilizer applied in the fall. These results suggest that the 10 percent tax imposed on fall nitrogen will reduce the total amount of nitrogen applied approximately by 3.9 percent, and a 10 percent tax on nitrogen fertilizer (fall and spring) will result in 2.6 percent reduction in the total amount of nitrogen demanded.

Appendices :

Appendix 1: Conditional posterior distribution

Using the augmented posterior from section 3.1, the conditional posterior for the parameter vector θ is given by:

$$
\begin{aligned}
p\left(\theta \middle| \tilde{y}^*, \Sigma\right) &\propto \exp\left(-\frac{1}{2}\left[\sum_{i=1}^{n}\left(\tilde{y}_i^* - X_i\theta\right)' \Sigma^{-1}\left(\tilde{y}_i^* - X_i\theta\right) + \left(\theta - \mu_{\theta_0}\right)' V_{\theta_0}'\left(\theta - \mu_{\theta_0}\right)\right]\right) \\
&\propto \exp\left(-\frac{1}{2}\left[\sum_{i=1}^{n}\left(\tilde{y}_i^{*\prime}\Sigma^{-1}\tilde{y}_i^* - 2\theta' X_i'\Sigma^{-1}\tilde{y}_i^* + \theta' X_i'\Sigma^{-1}X_i\theta\right)\right.\right. \\
&\qquad \left.\left. + \left(\theta' V_{\theta_0}^{-1}\theta - 2\theta' V_{\theta_0}^{-1}\mu_{\theta_0} + \mu_{\theta_0}' V_{\theta_0}^{-1}\mu_{\theta_0}\right)\right]\right) \\
&\propto \exp\left(-\frac{1}{2}\left[\theta'\left(\sum_{i=1}^{n} X_i'\Sigma^{-1}X_i + V_{\theta_0}^{-1}\right)\theta - 2\theta'\left(\sum_{i=1}^{n} X_i'\Sigma^{-1}\tilde{y}_i^* + V_{\theta_0}^{-1}\mu_{\theta_0}\right)\right]\right) \\
&\propto \exp\left(-\frac{1}{2}\left[\theta' V_{\theta_1}^{-1}\theta - 2\theta' V_{\theta_1}^{-1}\mu_{\theta_1}\right]\right) \\
&\propto \exp\left(-\frac{1}{2}\left[\theta' V_{\theta_1}^{-1}\theta - 2\theta' V_{\theta_1}^{-1}\mu_{\theta_1} + \mu_{\theta_1}' V_{\theta_1}^{-1}\mu_{\theta_1} - \mu_{\theta_1}' V_{\theta_1}^{-1}\mu_{\theta_1}\right]\right) \\
&\propto \exp\left(-\frac{1}{2}\left[\left(\theta - \mu_{\theta_1}\right)' V_{\theta_1}^{-1}\left(\theta - \mu_{\theta_1}\right)\right]\right)
\end{aligned}
$$

where $V_{\theta_1} = \left(\sum_{i=1}^{n} X_i'\Sigma^{-1}X_i + V_{\theta_0}^{-1}\right)^{-1}$ and $\mu_{\theta_1} = V_{\theta_1}\left(\sum_{i=1}^{n} X_i'\Sigma^{-1}y_i^* + V_{\theta_0}^{-1}\mu_{\theta_0}\right)$

Therefore,

$$p\left(\theta \middle| y^*, \Sigma\right) = N\left(\mu_{\theta_1}, V_{\theta_1}\right)$$

The conditional posterior for $\Sigma \middle| \theta, \tilde{y}^*$ is similarly derived from the augmented posterior,

$$
\begin{aligned}
p\left(\Sigma \middle| \tilde{y}^*, \theta\right) &\propto |\Sigma|^{-n/2} \exp\left(-\frac{1}{2}\sum_{i=1}^{n}\left(\tilde{y}_i^* - X_i\theta\right)' \Sigma^{-1}\left(\tilde{y}_i^* - X_i\theta\right)\right) \\
&\quad \times |\Sigma|^{-(b+n+1)/2} \exp\left(-tr\left(a\Sigma\right)^{-1}/2\right) \\
&\propto |\Sigma|^{-(b+2n+1)/2} \exp\left(-\frac{1}{2}\left[\sum_{i=1}^{n} tr\left(\tilde{y}_i^* - X_i\theta\right)\left(\tilde{y}_i^* - X_i\theta\right)' \Sigma^{-1} + tr\left(a\Sigma\right)^{-1}\right]\right)
\end{aligned}
$$

$$\propto |\Sigma|^{-(b+2n+1)/2} \exp\left(-\frac{1}{2} tr\left(\left[\sum_{i=1}^{n} \left(\tilde{y}_i^* - X_i\theta \right)\left(\tilde{y}_i^* - X_i\theta \right)' + a^{-1} \right] \Sigma^{-1} \right) \right)$$

Therefore,

$$\Sigma^{-1} \left| \tilde{y}_i^*, \theta \sim W\left(\left(\sum_{i=1}^{n} \left(\tilde{y}_i^* - X_i\theta \right)' \left(\tilde{y}_i^* - X_i\theta \right) + a \right)^{-1}, n+b \right) \right.$$

Appendix 2: **The posterior simulator**

The posterior simulator employs a Gibbs sampling procedure, drawing in turn from the conditional posterior distribution for $\theta, \Sigma,$ and $\tilde{y}^*$:

Step 0: Set $\left(\tilde{y}_i^*\right)^0 = \left[\left(F_i^*\right)^0 \left(Y_{Fi}^*\right)^0 \left(S_i^*\right)^0 \left(Y_{Si}^*\right)^0 \right]' = \left[F_i \;\, Y_{Fi} \;\, S_i \;\, Y_{Si} \right]'$ and

$$\Sigma^0 = 400 \times \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

Step 1: Draw θ^1 from the distribution given by (2.3.2) conditional on $\left(\tilde{y}_i^*\right)^0$ and Σ^0.

Step 2: Draw the elements of the covariance matrix Σ^1 conditional on θ^1 and $\left(\tilde{y}_i^*\right)^0$ using (2.3.3).

Step 3: Data augmentation step. Draw the latent data $\left(\tilde{y}_i^*\right)^1 = \left[\left(F_i^*\right)^1 \left(Y_{Fi}^*\right)^1 \left(S_i^*\right)^1 \left(Y_{Si}^*\right)^1 \right]'$ conditional on θ^1 and Σ^1:

a. Compute the errors ε_{2i}, ε_{3i} and ε_{4i} given θ^1 from *Step 1* and latent data $\left(Y_{Fi}^*\right)^0$, $\left(S_i^*\right)^0$, and $\left(Y_{Si}^*\right)^0$;

b. Draw $\left(F_i^*\right)^1$ from

$$TN_{[0,\infty)}\left(x_i\beta_1^1 + z_{1i}\alpha_1^1 + \sigma_{-1}^{1\,\prime}\left(\Sigma_{-11}^1\right)^{-1}\varepsilon_{-1}\,,\quad \left(\sigma_1^2\right)^1 - \sigma_{-1}^{1\,\prime}\left(\Sigma_{-11}^1\right)^{-1}\sigma_{-1}^1\right) \text{ if } F_i \ \ge 0$$

where Σ_{-ij} denotes the variance-covariance matrix Σ with row i and column j removed, σ_{-i} denotes the i^{th} column of the variance-covariance matrix Σ with i^{th} element removed, and, finally, ε_{-i} denotes the error vector with the i^{th} element removed.

$$TN_{(-\infty,0]}\left(x_i\beta_1^1 + z_{1i}\alpha_1^1 + \sigma_{-1}^{1\,\prime}\left(\Sigma_{-11}^1\right)^{-1}\varepsilon_{-1},\quad \left(\sigma_1^2\right)^1 - \sigma_{-1}^{1\,\prime}\left(\Sigma_{-11}^1\right)^{-1}\sigma_{-1}^1\right) \text{ if } F_i \ < 0$$

c. Compute the errors ε_{1i} given θ^1 from *Step 1* and latent data $\left(F_i^*\right)^1$;

d. Draw $\left(Y_{Fi}^*\right)^1$ from

$$N\left(x_{2i}\beta_2^1 + z_{2i}\alpha_2^1 + \sigma_{-2}^{1\,\prime}\left(\Sigma_{-22}^1\right)^{-1}\varepsilon_{-2}^1,\quad \left(\sigma_2^2\right)^1 - \sigma_{-2}^{1\,\prime}\left(\Sigma_{-22}^1\right)^{-1}\sigma_{-2}^1\right) \qquad \text{if } \left(F_i^*\right)^1 < 0$$

and set $Y_{Fi}^* = Y_{Fi}$ if $\left(F_i^*\right)^1 \ge 0$

e. Compute the errors ε_{2i} given θ^1 from *Step 1* and latent data $\left(Y_{Fi}^*\right)^1$;

f. Draw $\left(S_i^*\right)^1$ from

$$TN_{[0,\infty)}\left(x_{3i}\beta_3^1 + \delta_3^1 Y_{Fi}^{\,1} + \sigma_{-3}^{1\,\prime}\left(\Sigma_{-33}^1\right)^{-1}\varepsilon_{-3}^1,\quad \left(\sigma_3^2\right)^1 - \sigma_{-3}^{1\,\prime}\left(\Sigma_{-33}^1\right)^{-1}\sigma_{-3}^1\right) \text{ if } S_i \ \ge 0$$

$$TN_{(-\infty,0]}\left(x_{3i}\beta_3^1 + \delta_3^1 Y_{Fi}^{\,1} + \sigma_{-3}^{1\,\prime}\left(\Sigma_{-33}^1\right)^{-1}\varepsilon_{-3}^1, \left(\sigma_3^2\right)^1 - \sigma_{-3}^{1\,\prime}\left(\Sigma_{-33}^1\right)^{-1}\sigma_{-3}^1\right) \quad \text{if } S_i \ < 0$$

g. Compute the errors ε_{3i} given θ^1 from *Step 1* and latent data $\left(S_i^*\right)^1$ and $\left(Y_{Fi}^*\right)^1$;

h. Draw $\left(Y_{Si}^*\right)^1$ from

$$N\left(x_{4i}\beta_4^1 + \delta_4^1 Y_{Fi}^{\,1} + \sigma_{-4}^{1\,\prime}\left(\Sigma_{-44}^1\right)^{-1}\varepsilon_{-4}^1,\quad \left(\sigma_4^2\right)^1 - \sigma_{-4}^{1\,\prime}\left(\Sigma_{-44}^1\right)^{-1}\sigma_{-4}^1\right) \quad \text{if } \left(S_i^*\right)^1 < 0$$

and set $Y_{Si}^{*} = Y_{Si}$ if $\left(S_i^{*}\right)^1 \geq 0$.

i. Compute the errors ε_{4i} given θ^1 from *Step 1* and latent data $\left(Y_{Si}^{*}\right)^1$ and $\left(Y_{Fi}^{*}\right)^1$;

Step 4: Repeat steps 1-3 K times.

The Gibbs algorithm generates a sample of size K from conditional posterior distribution of each of the parameters of the model. The first K_0 draws are discarded as burn-in, the remaining $K_1 = K - K_0$ draws are used for the analysis.

References

[1] Abler, D. G., James S. Shortle. "Technology as an Agricultural Pollution Control Policy". *American Journal of Agricultural Economics*. 77 (1995): 20-32.

[2] Albert, J., S. Chib. "Bayesian Analysis of Binary and Polychotomous Response Data". *Journal of the American Statistical Association*. 88 (1993): 669-679.

[3] Babcock, B.A. "The Effect of Uncertainty on Optimal Nitrogen Application". *Review of Agricultural Economics*. 14 (1992): 271-280.

[4] Babcock, B.A., A.M. Blackmer. "The Ex Post Relationship between Growing Conditions and Nitrogen Fertilizer Levels". *Review of Agricultural Economics*. 16 (1994): 441-450.

[5] Blackmer, A.M. "Losses of Fall-Applied Nitrogen". In *Proc. Annual Integrated Crop Management Conference.* Iowa State University. Ames, IA. 29-30 Nov. 1995. 55-59.

[6] Blackmer, A.M. "Bioavailability of Nitrogen". In M. E. Sumner (ed.) *Handbook of soil science.* CRC Press. Boca Raton. FL. 2000. D3-D18.

[7] Bontems, P., A. Thomas. "Information Value and Risk Premium in Agricultural Production: The Case of Split Nitrogen Application for Corn". *American Journal of Agricultural Economics.* 82:1 (2000): 59-70.

[8] Bosch, D. J., Z. L. Cook, K. O. Fuglie. "Voluntary versus Mandatory Agricultural Policies to Protect Water Quality: Adoption of Nitrogen testing in Nebraska". *Review of Agricultural Economics*. 17 (1995): 13-24.

[9] Bundy, L. G., T. W. Andraski, and R. P. Wolkowski. "Nitrogen Credits in Soybean-Corn Crop Sequences on Three Soils". *Agronomy Journal.* 85 (1993): 1061-1067.

[10] Caswell, M., D. Zilberman. "The Choices of Irrigation Technology in California". *American Journal of Agricultural Economics*. 67 (1985): 224-234.

[11] Cooper, J. C., R. W. Keim. “Incentive Payments to Encourage Farmer Adoption of Water Quality Protection Practices”. *American Journal of Agricultural Economics*. 22 (1996): 54-64.

[12] Deb, P., M. K. Munkin, P. K. Trivedi. “Bayesian Analysis of the Two-Part Model with Endogeneity: Application to Health Care Expenditure”. *Journal of Applied Econometrics.* 21:7 (2006): 1081-1099.

[13] Denbaly, M., and H. Vroomen. “Elasticities of Fertilizer Demands for Corn in the Short and the Long Run. A Cointegrated and Error Correcting System”. *American Journal of Agricultural Economics*. 75 (1993): 203-209.

[14] Dillon, C. “Production Practice Alternatives for Income nd Suitable Field Day Risk Management”. *Journal of Agricultural and Applied Economics.* 31 (1999): 247-261.

[15] Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. “Nitrogen Management Strategies to Reduce Nitrate Leaching in Tile-Drained Midwestern Soils”. *Agronomy Journal.* 94 (2002): 153-171.

[16] Feinerman, E., E. K. Choi, S. R. Johnson. “Uncertainty and Split Nitrogen Application in Corn Production”. *American Journal of Agricultural Economics.* 72 (1990): 975-984.

[17] Fletcher, J. J., A. M. Featherstone. “An Economic Analysis of Tillage and Timeliness Interactions in Corn-Soybean Production”. *North Central Journal of Agricultural Economics*. 9 (1987): 207-215.

[18] Fuglie, K.O., D.J. Bosch. “Economic and Environmental Implications of Soil Nitrogen Testing: A Switching-regression Analysis”. *American Journal of Agricultural Economics*. 77 (1995): 891-900.

[19] Gentry, L. E., F.E. Below, M.B. David, J. A. Bergerou. “Source of the Soybean N Credit in Maize Production”. *Plant and Soil*. 236 (2001): 175-84.

[20] Geweke, J. “Efficient Simulation from the Multivariate Normal and Student-t Distributions Subject to Linear Constraints”. In Keramidas E. M. (ed.) *Computing Science and Statistics: Proceedings of the 23rd Symposium on the Interface*. (1991): 571-578.

[21] Griliches, Z. “Agricultural Output and the Demand for Input: The Demand for Inputs in Agriculture and a Derived Supply Elasticity” *Journal of Farm Economics*. 41 (1959): 309-322.

[22] Griliches, Z. “The Demand for Fertilizer: An Economic Interpretation of a Technical Change”. *Journal of Farm Economics*. 40 (1958): 591-606.

[23] Hertel, T.W. and K.W Stiegert. “Managerial heterogeneity and the compositional effect”. *Applied Economics Letters*. 7 (2000): 271 -274.

[24] Hertel, T.W., K.W Stiegert. And H. Vroomen. “Nitrogen-Land Substitution in Corn Production: A Reconciliation of Aggregate and Firm Level Evidence”. *American Journal of Agricultural Economics.* 78 (1996): 30-40.

[25] Huang, W., L. Hansen, N.D. Uri. "The Application Timing of Nitrogen Fertilizer". *Water, Air, and Soil Pollution,* 73 (1994): 189-211.

[26] Huang, W., R.G. Heifner, H. Taylor, and N. D. Uri. "Timing Nitrogen Fertilizer Application to Reduce Nitrogen Losses to the Environment". *Water Resource Management.* 14 (2000): 35-58.

[27] Huang, W., T.I. Hewitt, and D. Shank. "An Analysis of On-Farm Costs of Timing N Applications to Reduce N Losses". *Journal of Agricultural and Resource Economics.* 23:2 (1998): 445-467.

[28] Huang, W., L., R. W. Keim, Y. Lu, N. D. Uri, T. Kelley. "The Impact of Nitrogen Carryover Effect on Economic Activity and the Environment". *Environmental Geology.* 34 (1998): 116-127.

[29] Huang, W., N. D. Uri. "A Note on Nitrogen Fertilizer Application Timing". *Applied Mathematical Modeling.* 19 (1995): 35-58.

[30] Iowa State University Extension. "Fieldwork Days in Iowa". 2007a. (online: http://www.extension.iastate.edu/ Publications /PM1874.pdf)

[31] Iowa State University Extension. "Managing Manure Nutrients for Crop Production". 2003. (online: http://www.extension.iastate.edu/Publications/PM1811.pdf)

[32] Iowa State University Extension. "Nitrogen Fertilizer Recommendations for Corn in Iowa". 2007b. (online: http://www.extension.iastate.edu/Publications/PM1714.pdf)

[33] Koop, G., D. J. Poirier, J. L. Tobias. *Bayesian Econometric Methods*. Cambridge University Press. 2007.

[34] Kurkalova, L., C. L. Kling and J. Zhao. "Green Subsidies in Agriculture: Estimating the Adoption Costs of Conservation Tillage from Observed Behavior". *Canadian Journal of Agricultural Economics.* 54 (2006): 257-267.

[35] Li, M., D. J. Poirier, and J. L. Tobias. "Do Dropouts Suffer from Dropping Out? Estimation and Prediction of Outcome Gains in Generalized Selection Models". *Journal of Applied Econometrics*. 19 (2004): 203-225.

[36] Lichtenberg, E. "Cost-Responsiveness of Conservation Practice Adoption: A Revealed Preference Approach". *Journal of Agricultural and Resource Economics*. 29 (2004): 420-435.

[37] McCulloch, R. E., N. G. Polson, P. E. Rossi. "A Bayesian Analysis of the Miltinomial Probit Model with Fully Identified Parameters". *Journal of Econometrics*. 99 (2000): 173-193.

[38] McCulloch, R. E., P. E. Rossi. "An Exact Likelihood Analysis of the Miltinomial Probit Model". *Journal of Econometrics*. 64 (1994): 207-240.

[39] Munkin, M., P. K. Trivedi. "Bayesian Analysis of a Self-Selection Model with Multiple Outcomes Using Simulation-Based Estimation: an Application to the Demand for Healthcare". *Journal of Econometrics*. 114 (2003): 197-220.

[40] Nobile, A. “Comment: Bayesian Multinomial Probit Models with a Normalization Constraint”. *Journal of Econometrics*. 99 (2000): 335-345.

[41] Onianwa, O., R. Alderfer, R. A.Levins. ”Taxation as a Means of Reducing Nitrogen Fertilizer Use in Minnesota Corn Production”. University of Minnesota. Department of Applied Economics. Staff Paper P92-15. 1992.

[42] Panel to Review USDA's Agricultural Resource Management Survey, National Research Council. *Understanding American Agriculture: Challenges for the Agricultural Resource Management Survey.* National Academy of Scinces. 2007.

[43] Poirier, D. J., J. L. Tobias. “On the Predictive Distributions of Outcome Gains in the Presence of an Unidentified Parameter”. *Journal of Business and Economic Statistics*. 21 (2003): 258-68.

[44] Randall, G.W., M. A. Schmitt. ”Advisability of Fall-Applying Nitrogen”. In *Proceedings of 1998 Wisconsin Fertilizer, Aglime, and Pest Management Conference.* University of Wisconsin, Madison, WI. 1998. 90–96.

[45] Randall, G.W., J. A. Vetsch, and J. R. Huffman. “Nitrate Losses in Subsurface Drainage from a Corn–Soybean Rotation as Affected by Time of Nitrogen Application and Use of Nitrapyrin”. *Journal of Environmental Quality*. 32 (2003): 1764–1772.

[46] Roberts, R. “Plant Nutrient Demand Functions for Tennessee with Prices of Jointly Applied Nutrients”. *Southern Journal of Agricultural Economics*.18 (1986): 107-112.

[47] Roberts, R. and E. O. Heady. “Fertilizer Demand Functions for Specific Nutrients Applied to Three Major U. S. Crops”. *Western Journal of Agricultural Economics*. 7 (1982): 265-277.

[48] Rotz, C. A., T. M. Harrigan. “Predicting Suitable Days for Field Operations in a Whole Farm Simulation*”. An ASAE/CSAE Meeting Presentation Paper Number: 04303.* Ottawa, Ontario, Canada. August 2004.

[49] Sharpley, A., J.J. Meisinger, A. Breeuwsma, J.T. Sims, T.C. Daniel, and J.S. Schepers. ”Impacts of Animal Manure Management on Ground and Surface Water Quality”. *In* J.L. Hatfield and B.A. Stewart (ed.) *Animal waste utilization: Effective use of manure as a soil resource.* Ann Arbor Press. Chelsea. MI. 1998. 173–242.

[50] Soule, M. J. “Soil Management and the Farm Typology: Do Small Family Farms Manage Soil and Nutrient Resources Differently than Large Family Farms?” *Agricultural and Resource Economic Review*. 30 (2001): 179-188.

[51] Tanner, M. A., Wong, W. H. “The Calculation of Posterior Distributions by Data Augmentation (with Discussion)”. *Journal of the American Statistical Association*. 82 (1987): 528-550.

[52] Tobias, J. L. “Estimation, Learning and Parameters of Interest in a Multiple Outcome Selection Model”. *Econometric Reviews*. 25 (2006): 1-40.

[53] Uri, N. D. “Environmental considerations in fertilizer use decision”. *Environmental Geology.* 34 (1998a): 103-110.

[54] Uri, N. D. “The Environmental Consequences of the Conservation Tillage Adoption Decision in Agriculture in the United States”. *Water, Air, and Soil Pollution*. 103 (1998b): 9-33.

[55] University of Nebraska-Lincoln Extension. “Determining Crop Available Nutrients from Manure”. 2006. (online: http://www.ianrpubs.unl.edu/epublic/pages/index.jsp?what= publicationD&publicationId=494).

[56] University of Minnesota Extension. “Manure is a Good Source of Nitrogen”. 2008. (online: http://www.extension.umn.edu/distribution/cropsystems/DC5760.html).

[57] USDA.. ERS. 2001. (online: http://www.ers.usda.gov/publications/aer792/aer792c.pdf)

[58] Vroomen, H., and B. Larson. “A Direct Approach for Estimating Nitrogen, Phosphorus, and Land Demands at the Regional Level”. USDA. ERS Technical Bulletin No. 1786. 1991.

[59] Wu, J., R.M. Adams, C.L. Kling, K. Tanaka. “From Microlevel Decisions to Landscape Changes: An Assessment of Agricultural Conservation Policies”. *American Journal of Agricultural Economics*. 86 (2004): 26-41.

[60] Wu, J., 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.

[61] Wu, J., K. Tanaka. “Reducing Nitrogen Runoff from the Upper Mississippi River Basin to Control Hypoxia in the Gulf of Mexico: Easements or Taxes?”. *Marine Resource Economics*. 20 (2005): 121-44.

[62] Yen, S. T. “A Multivariate Sample-Selection Model: Estimating Cigarette and Alcohol Demands with Zero Observations”. *American Journal of Agricultural Economics.* 87 (2005): 453-466.

Table 2.1. Definitions of Variables

Variables	Definition	Fall	Spring
Fall fertilizer application	Fertilizer applied in fall (1=yes, 0=no)	X	
Early spring fertilizer application	Fertilizer applied in early spring (1=yes, 0=no)		X
Nitrogen application rate in fall	Amount of nitrogen applied (pounds)	X	
Nitrogen application rate in spring	Amount of nitrogen applied (pounds)		X
College education	Farm operator had some college education (1=yes, 0=no)	X	X
Off-farm employment	Farmer worked off-farm (1=yes, 0=no)	X	
Field acreage	Number of acres in farm	X	X
Land capability class	Land capability class is 1 or 2 (1=yes, 0=no)	X	X
Manure applied	Manure was applied in field (1=yes, 0=no)	X	X
Rotation	Corn was rotated with a legume crop (1=yes, 0=no)	X	X
Fieldwork days in fall	Number of days available for a fieldwork	X	
Fieldwork days in spring	Number of days available for a fieldwork		X
Fertilizer price in fall	Fertilizer price in fall ($/lb)	X	
Fertilizer price in spring	Fertilizer price in spring ($/lb)		X

Table 2.2. Descriptive Statistics of Variables

	Units	Mean	St. dev.
Fall fertilizer application	Number	0.18	0.012
Early spring fertilizer application	Number	0.72	0.026
Nitrogen application rate in fall	Lb/acre	83.46	3.64
Nitrogen application rate in spring	Lb/acre	132.5	2.86
College education	Number	0.40	0.015
Off-farm employment	Number	0.60	0.046
Field acreage	Acres	68.45	1.425
Land capability class	Number	0.74	0.04
Manure applied	Number	0.18	0.004
Rotation	Number	0.73	0.012
Fieldwork days in fall	Days	20.64	2.125
Fieldwork days in spring	Days	16.48	1.98
Fertilizer price in fall	$ per lb	0.14	0.01
Fertilizer price in spring	$ per lb	0.199	0.02
Dummy for IL	Number	0.28	0.09

Dummy for IN	Number	0.28	0.07
Dummy for OH	Number	0.27	0.08

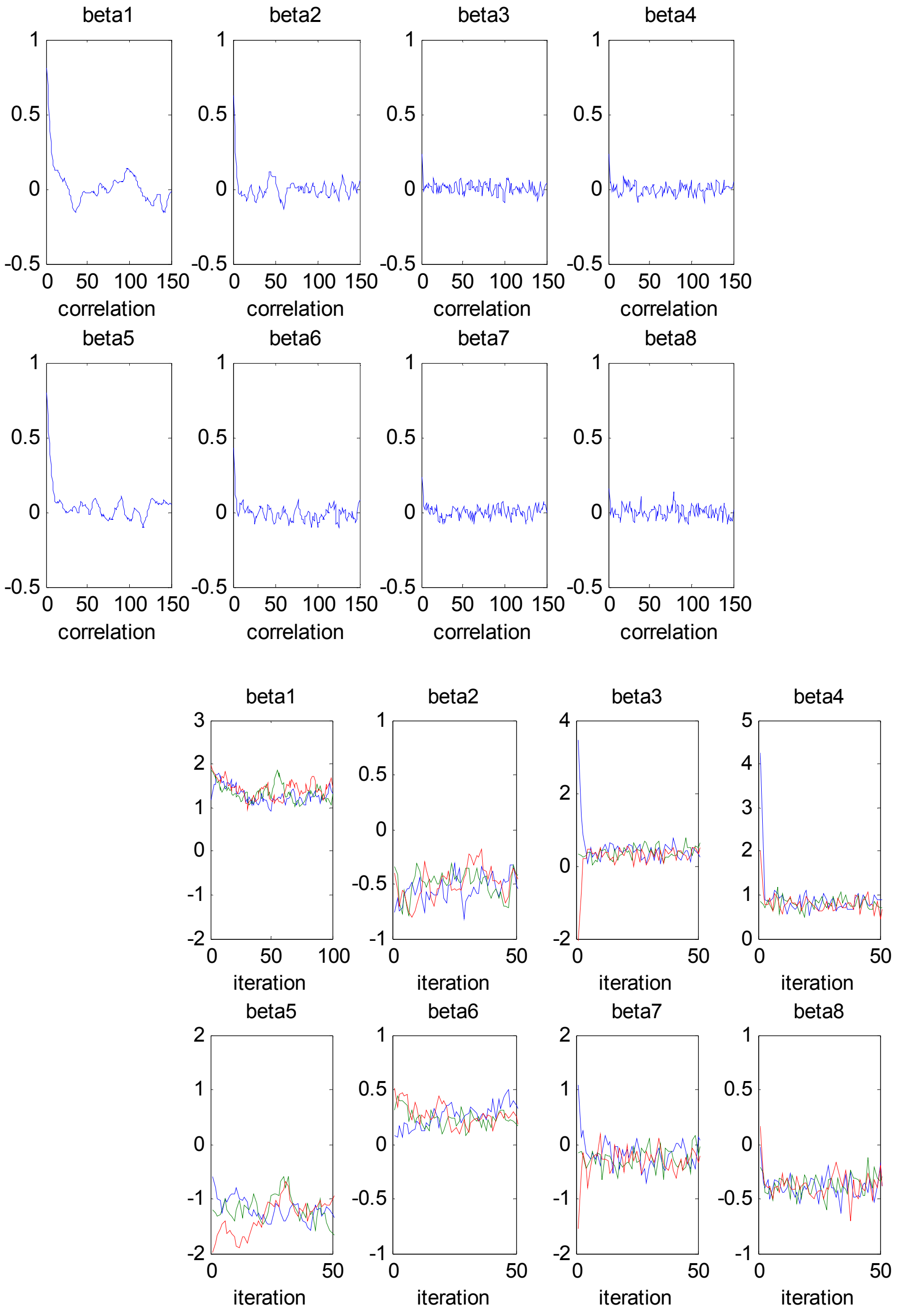
Table 2.3a. Results: Posterior Means, Standard Deviations, and Probabilities of Being Positive.

Variables	Fall Application			Fall Application Rate		
	Mean	Std.	$\Pr(\cdot > 0 \mid y)$	Mean	Std.	$\Pr(\cdot > 0 \mid y)$
Intercept	2.21	0.68	1	3.54	1.21	1
College education	-0.023	0.01	0.13	-2.4	1.35	0.22
Off-farm employment	0.28	0.01	0.90			
Field acreage	0.92	0.05	0.97	0.30	0.061	0.94
Land capability class	0.54	0.23	0.94	0.35	0.22	0.84
Manure applied	-0.024	0.008	0.13	-34.45	2.58	0.15
Rotation	-0.15	0.04	0.07	-20.03	1.47	0.01
Fieldwork days in fall	0.19	0.03	0.99	1.64	0.86	0.97
Fertilizer price in fall	-0.43	0.29	0.25	-1.47	1.36	0.22
Dummy for IL	0.03	0.04	0.85	0.001	0.001	0.84
Dummy for IN	-0.24	0.10	0.17	-0.02	0.003	0.08
Dummy for OH	-0.22	0.10	0.09	-0.023	0.015	0.06

Table 2.3b. Results: Posterior Means, Standard Deviations, and Probabilities of Being Positive.

Variables	Spring Application			Spring Application Rate		
	Mean	Std.	$\Pr(\cdot > 0 \mid y)$	Mean	Std.	$\Pr(\cdot > 0 \mid y)$
Intercept	3.27	0.68	1	1.64	0.46	1
College education	0.04	0.02	0.82	1.32	0.90	0.84
Field acreage	0.05	0.007	0.93	-0.96	0.59	0.14
Land capability class	0.73	0.58	0.95	0.44	0.44	0.96
Manure applied	-0.03	0.004	0.11	-46.32	0.62	0.08
Rotation	-0.14	0.03	0.09	-28.79	2.92	0.11
Fieldwork days in spring	0.15	0.42	0.97	0.68	0.66	0.93
Fertilizer price in spring	-0.013	0.009	0.17	-1.32	0.90	0.13
Nitrogen application rate in fall	-0.23	0. 09	0.11	-2.48	1.68	0.09
Dummy for IL	-0.13	0.07	0.17	-0.14	0.10	0.13
Dummy for IN	-0.21	0.09	0.05	-0.32	0.12	0.08
Dummy for OH	-0.16	0.11	0.13	-0.18	0.06	0.09

Figure 2.7. Model Diagnostics.



CHAPTER 3: DECISIONS ON TIMING OF FERTILIZER APPLICATION AND TILLAGE SYSTEM: IMPLICATIONS FOR NITROGEN PRODUCTIVITY.

3.1. Introduction

Nonpoint loss of nitrogen from fields to water resources is not caused by any single factor. Rather, it is caused by a combination of factors. Choices of tillage and nitrogen management (type of tillage, timing of tillage, timing of nitrogen application, and nitrogen rate) have a significant effect on nitrogen use by corn and nitrate movement through the soil. A tillage survey sponsored by the Iowa Resource Management Partnership committee in 1999 indicated the need for an integrated approach in the adoption of best management practices for nutrients, tillage, and crop residue (Al-Kaisi and Hanna, 2005). Such integration of tillage and nitrogen management is important for both water quality and soil productivity.

One reason for considering tillage and fertilizer application decisions jointly is that nitrogen fertilizer management can be greatly affected by changes in tillage. For example, conservation tillage systems may increase nitrogen immobilization and its losses from leaching, denitrification, and volatilization (Gilliam and Hoyt, 1987; Wood and Edwards, 1992). Since no-till soils usually have higher water content than soils managed by conventional tillage, the leaching of nitrogen through macropores becomes a bigger problem (Priebe and Blackmer, 1989). Moreover, research shows that soil moisture and temperature (cooler and wetter soil under conservation tillage) impact both soil nitrogen dynamics (Torbert and Wood, 1992) and early corn growth (Beyaert, Schott, and White, 2002; Al-Kaisi and Hanna, 2005; Halvorson *et al*., 2006). Overall, immobilization of nitrogen and its losses from leaching, denitrification, and volatilization associated with use of conservation tillage result in lower efficiency of applied nitrogen.

One concern regarding these interactions between tillage and nitrogen efficacy is that, in order to offset the negative effects of nitrogen deficiency on crop yields, farmers might increase the amount of nitrogen fertilizer applied compared to conventional tillage. Indeed, in their study Randall and

Bandel (1991) showed that in conservation tillage fertilizer nitrogen rates have been increased by as much as 25% to prevent yield limitations from nitrogen immobilization. Moreover, higher nitrogen application rates associated with conservation tillage might increase farmer's risk of not being able to finish everything on time and drive up opportunity cost of time for farmer during planting season. As a result, farmers utilizing conservation tillage are more inclined to apply fertilizer in fall. Indeed, results of the 1996 Agricultural Resource Management Survey (ARMS) data for U.S. corn farms and producers highlighted how tillage systems seemed to influence different nutrient management practices, including the timing of fertilizer application (Christensen, 2002). It was found that a greater share of acres in no-till than in conventional tillage received nitrogen in the fall prior to planting, with a smaller percentage in the spring at or before planting, but the influence of these soil tillage systems on fertilizer nitrogen rates in corn production was not determined.

Several studies have considered the issues related to adoption of practices aimed at reducing nutrient losses from agricultural fields and improving water quality, including conservation tillage (Korsching *et al*., 1983; Kurkalova, Kling, and Zhao, 2006; Wu and Babcock, 1998; Wu *et al.,* 2004; Uri, 1998; Fuglie, 1999). Researchers and policy makers are concerned about their low adoption rate. Khanna, Epouhe, and Hornbaker (1999) reported low adoption rates (around 20%) for soil testing and variable-rate application in Wisconsin, Iowa, and Illinois. One explanation of low adoption rate is that farmers fear that these practices may reduce their yields. There are several factors that may affect farmers' perception that adoption of a particular practice may lead to a decrease in yield. For example, if additional field operations are required, this activity may delay other farm activities that must be completed within that time of year.

There are, however, three important issues related to fall fertilizer and tillage choice that have not been addressed in the past. First, the overall question of fall fertilizer application (relative to spring) has received little attention in empirical literature. Past work concentrates on analysis of split fertilizer application where farmers' apply nitrogen fertilizer in the spring before planting vs. during the growing season. Second, the previous literature on this topic has not considered the possible relationship between a farmers' decisions regarding tillage choice and fall fertilizer application. Since factors affecting the farmer's decision regarding tillage may influence their decision regarding fall fertilizer applications, both decisions should be considered jointly. Econometrically, recognition of the interrelationships between decisions on timing of fertilizer application and tillage choice is important for obtaining consistent and more efficient estimates of parameters of the output equation. Third, the previous literature on this topic mostly focused on the effect of timing of fertilizer application on nitrogen application levels but there is lack of empirical evidence on effect of timing of fertilizer application on subsequent yields.

The goals of this chapter are twofold. First, I seek to determine which factors influence the use of fall fertilizer application and conservation tillage in a modeling framework that recognizes the interrelationship between the two decisions. Second, I examine the implications of adopting these two practices for nitrogen productivity, which is measured by crop yield. One of the main hypothesis of the proposed model is that the decisions on the timing of fertilizer application and tillage choice are interrelated. Conservation tillage is associated with fall fertilizer application. Therefore, I expect positive sign on the correlation term between unobservables in fertilizer timing and tillage choice equations.

The chapter proceeds as follows. The next section describes previous research on the topic, followed by a section 3 that describes the model used for individual farmer's decision making and the associated Bayesian posterior simulator. The data used in the analysis are described in section 5, followed by a description of empirical results in 6th and 7th sections. Finally, the chapter concludes with a summary of findings.

3.2. Previous Literature

There is a considerable agronomic literature concerning the timing of fertilizer application, the choice of tillage practices, and their subsequent impact on yields. For example, with regards to fall fertilizer application, the 2–3 months between application and nitrogen uptake create the potential for significant nitrogen losses. These nitrogen losses, in turn, create conditions where nitrogen becomes deficient and crop productivity declines. Several studies have evaluated the effect of the time of nitrogen application on nitrate losses and crop yields (Randall and Mulla, 2001; Buzicky *et al*., 1983; Randall, Vetsch, and Huffman, 2003; Randall and Vetch, 2003; Randall and Vetch, 2005; Al-Kaisi and Licht, 2004). In each case, nitrogen was applied in the fall (early November) and spring (late April) for continuous corn to determine the effect of nitrogen application time and rate on nitrate losses and corn yields. The results show that, averaged over the period of study, corn yields were significantly reduced with fall fertilizer application and nitrogen losses were greatest for fall applied nitrogen.

There is also a substantial literature on the adoption and efficacy of conservation tillage. Researchers consistently recommend conservation tillage systems following soybeans in Corn Belt region because previous research has shown them to be economically, environmentally, and agronomically effective (Vetsch and Randall, 2004; Uri, Atwood, and Sanabria, 1999; Uri, 1998). Leaving the residue in the field is beneficial for reducing erosion, improving the soil physical condition, maintaining lower soil temperatures during hot weather, improving the micro-environment above the soil, and for improving the soil water infiltration and holding capacity.

At the same time, minimum tillage slows early corn growth and reduces grain yields in some cases due to wet and cold, early season soil conditions (Beyaert, Schott, and White, 2002; Al-Kaisi, Hanna, 2005; Halvorson *et al*., 2006). Moreover, spring, preplant application of nitrogen fertilizer to corn under a no tillage system is often considered undesirable by growers because of delayed planting, which can result in yield reductions. Randall and Hill (2000) showed that strip tillage for corn after soybean in the northern Corn Belt is preferred in the fall immediately after soybean harvest due to more favorable and drier soil conditions, over-winter settling of soil in the tilled area, and a warmer and drier seedbed ideal for early planting in the spring.

A number of agronomic studies have looked at the combined effects of tillage systems and nitrogen application timing on overall crop production. Vetsch and Randall (2004) examined the effects of four tillage systems and two nitrogen application times on corn production following soybean. Al-Kaisi and Licht (2004) evaluated the effects of strip tillage and fertilizer application timing on corn yield and nitrate movement through the soil. Both studies showed the corn yields were significantly lower when fertilizers were applied in the fall rather than the spring application. At the same time, tillage choice had no significant effect on corn yields in study by Al-Kaisi and Licht. Vetsch and Randall found no significant interaction between the tillage system and the application time of nitrogen, indicating that the effect of fall versus spring application on corn production was the same for all tillage systems.

In general, past studies of practice adoption focused on either a single practice or on a set of practices considered as a single unit. In each case, independently defined univariate logit or probit models were used to examine the adoption decision for each practice or set of new practices. This ignores the possibility that practices may be substitutes or compliments. When practices are interrelated, as might be case of tillage choice and timing of fertilizer application, single equation models are inefficient because they ignore the correlation in the error terms of equations explaining the adoption decisions for these practices. Additionally, they ignore the possibility that a decision to adopt a particular practice may be conditional on the adoption of another complementary practice. Dorfman (1996) applied multinomial probit for modeling adoption decisions by farmers facing two technologies. His model allows for full analysis of the interaction between decisions to adopt these two technologies, however, his model does not consider implications of adoption decisions on production process.

In most empirical research on the adoption of site-specific practices and their implications for the nitrogen productivity, two-stage methods were used. Khanna (2001) investigated the sequential decision to adopt two site-specific practices, soil testing and variable rate technology, and the impact of adoption on nitrogen productivity. The two-stage procedure gives consistent estimates of the model coefficients (Maddala, 1983, p. 244), but the estimates of variances of the coefficients may be inconsistent because predicted values of endogenous variables are used in the second stage of the estimation. Bayesian framework used in this research eliminates these problems and results in consistent estimates.

3.3. The Model

There are three components to the model analyzed in this chapter: (1) a model of fall fertilizer application; (2) a model of conservation tillage adoption; and (3) a model of crop yields as a function of these first two decisions. In this section, I discuss each component of the model in turn, starting with the decision of fall fertilizer usage. Section 4 then provides the estimation procedures employed.

As in chapter 2, a double-hurdle approach is employed for modeling individual farmer's decision making on whether to apply fertilizer in fall and how much to apply. It is an extension to Heckman's selectivity model, which explicitly models non-participation and potential participation apart from the quantity decision. Advantages of using double hurdle model for adoption models with sample selection problems are discussed by Cooper and Keim (1996) and Uri (1998). Recent Bayesian treatments of the approach can be found in Deb, Munkin, and Trivedi (2006), Koop *et al.* (2007), Munkin, and Trivedi (2003).

According to the logic of the double-hurdle models, farmers must pass two separate hurdles before they are observed with a positive level of fertilizer application. These two hurdles are the outcome of farmer's choice: a participation decision (whether to apply fertilizer in the fall) and a consumption decision (how much to apply). Following Koop *et al.* (2007) the participation decision of farmer *i* is assumed to be driven by a latent variable F_i^*, with

$$F_i^* = x_{1i}\beta_1 + z_{1i}\alpha_1 + \varepsilon_{1i}$$

where x_{1i} and z_{1i} are exogenous factors (such as education, land characteristics and fertilizer prices) assumed to influence the participation decision, β_1 and α_1 are parameter vectors to be estimated, and

ε_{1i} captures unobserved attributes influencing the farmer's decision. The distinction between x_{1i} and z_{1i} is that the latter variables do not enter the subsequent tillage and yield variables and, hence, serve as instrumental variables. While the latent variable is not observed, we do observe the binary outcome F_i, where:

$$F_i = \begin{cases} 1, & F_i^* > 0 \\ 0, & F_i^* \le 0 \end{cases}$$

The fall fertilizer consumption decision is similarly driven by a latent variable Y_{Fi}^*, where

$$Y_{Fi}^* = x_{2i}\beta_2 + z_{2i}\alpha_2 + \varepsilon_{2i}\,.$$

However, fertilizer application levels are only observed if the farmer has passed the participation hurdle; i.e., we observe

$$Y_{Fi} = \begin{cases} Y_{Fi}^* & \mathit{if}\ F_i^* > 0 \\ 0 & \text{otherwise} \end{cases}$$

The decision as to whether or not to adopt conservation tillage is modeled using a standard probit framework. Specifically, T_i^* is the latent variable for choice of tillage system. The binary observed outcome variable T_i is obtained from latent variable associated with choice of conservation tillage in the following way:

$$T_i = \begin{cases} 1, & T_i^* > 0 \\ 0, & T_i^* \le 0 \end{cases} \quad \text{where} \quad T_i^* = x_{3i}\beta_3 + z_{3i}\alpha_3 + \varepsilon_{3i}$$

Crop yields are modeled as a censored regression, dependent on the both the amount of fall fertilizer usage and the tillage decision. Formally, Y_i^* is a latent variable governing the crop yield. Yield function is truncated at zero and is given by:

$$Y_i = \begin{cases} Y_i^*, & Y_i^* > 0 \\ 0, & Y_i^* \le 0 \end{cases} \quad \text{where} \quad Y_i^* = x_{4i}\beta_4 + \delta Y_{Fi} + \eta T_i + \varepsilon_{4i}$$

The error vector $\varepsilon_{\bullet i} = \left(\varepsilon_{1i}, \varepsilon_{2i}, \varepsilon_{3i}, \varepsilon_{4i}\right)'$ is assumed to be normally distributed, allowing for possible correlations among the unobservables driving the fertilizer application, tillage choice decisions, and yield; i.e., $\varepsilon_{\bullet i} \sim N\left(0, \Sigma\right)$ with

$$\Sigma = \begin{pmatrix} \sigma_1^2 & \sigma_{12} & \sigma_{13} & \sigma_{14} \\ & \sigma_2^2 & \sigma_{23} & \sigma_{24} \\ & & \sigma_3^2 & \sigma_{34} \\ & & & \sigma_4^2 \end{pmatrix}.$$

These possible correlations imply that instrumental variables are required for identification of the parameters in the full model. These are labeled as z_{1i} and z_{2i} in the fall fertilizer latent variable equations and z_{3i} in tillage choice equation.

Decisions on timing of fertilizer application and on choice of tillage system are assumed to be made by farmer simultaneously. Results of both decisions are assumed to affect farm yield so the model to investigate this problem falls into the category of treatment effect models. The binary decision on choice of conservation tillage is included in the mean function of outcome so the coefficient of it is referred to as the causal impact of the tillage treatment on Y. However, for fall fertilizer application only the amount of fertilizer applied is assumed to affect yield and included into the yield equation. Correlation in the unobservable factors influencing both the fall fertilizer and tillage decisions are captured by correlation coefficients σ_{13} and σ_{23} . The sign of these coefficients show the nature of the relationship between two practices. It is anticipated that no-till soils receive more nitrogen in the fall prior to planting when compared to conventional tillage. Therefore, I expect to observe positive correlation between tillage system and fall fertilizer application, i.e. $\sigma_{13} > 0$. Also, farmers increase fertilizer nitrogen rates with conservation tillage to prevent yield reductions from nitrogen immobilization, leaching, and denitrification. Therefore, I expect to observe positive correlation between tillage system and fall fertilizer application rate, i.e. $\sigma_{23} > 0$, as well.

3.4. Estimation Details

I estimate the model derived in Section 3 using a Bayesian framework, combining data augmentation and Gibbs sampling procedures. In this section, an outline of the derivation of the posterior distribution and the sampling routine is presented, relegating details of the sampler to an appendix.

3.4.1. Posterior Distribution

The full system of equations to be estimated is given by:

$$\begin{aligned} F_i^* &= x_{1i}\beta_1 + z_{1i}\alpha_1 + \varepsilon_{1i} \\ Y_{Fi}^* &= x_{2i}\beta_2 + z_{2i}\alpha_2 + \varepsilon_{2i} \\ T_i^* &= x_{3i}\beta_3 + z_{3i}\alpha_3 + \varepsilon_{3i} \\ Y_i^* &= x_{4i}\beta_4 + \delta Y_{Fi} + \eta T_i + \varepsilon_{4i} \end{aligned} \tag{3.4.1}$$

Since F_i^* and T_i^* in the participation equations are unobservable, only the ratios $\frac{\beta_1}{\sigma_1}$, $\frac{\alpha_1}{\sigma_1}$, $\frac{\beta_3}{\sigma_3}$, and $\frac{\alpha_3}{\sigma_3}$ are identified. One way to deal with identification problem is to restrict the error variances in participation equations to unity. McCulloch, Polson and Rossi (2000) provide the Bayesian analysis of the multinomial probit model, which incorporates the identification constraint by setting the one diagonal element of the covariance matrix equal to one. Nobile (2000) proposes way to generate Wishart and inverted Wishart random matrices conditional on one of the diagonal elements.

However, since (3.4.1) contains two participation equations, it would require imposing two constraints on the diagonal elements of the covariance matrix: $\sigma_1 = 1$ and $\sigma_3 = 1$. Therefore, I follow McCulloch and Rossi (1994) approach where a proper prior is specified for the full set of parameters (θ, Σ) and the marginal posterior distributions of the identified parameters (β_1 / σ_1, α_1 / σ_1, β_3 / σ_3, and α_3 / σ_3) are reported. Thus, the prior on the identified parameters is the marginal prior of (β_1 / σ_1, α_1 / σ_1, β_3 / σ_3, and α_3 / σ_3) derived from the prior distribution specified for the full set of parameters (θ, Σ). The approach is taken because of the difficulties associated with a Bayesian analysis of covariance matrices with multiple constraints.

The four equations for each individual are stacked in the following manner:

$$\tilde{y}_i^* = \begin{pmatrix} F_i^* \\ Y_{Fi}^* \\ T_i^* \\ Y_i^* \end{pmatrix}_{4\times 1}, \quad \tilde{y}_i = \begin{pmatrix} F_i \\ Y_{Fi} \\ T_i \\ Y_i \end{pmatrix}_{4\times 1}, \quad e_i = \begin{pmatrix} \varepsilon_{1i} \\ \varepsilon_{2i} \\ \varepsilon_{3i} \\ \varepsilon_{4i} \end{pmatrix}_{4\times 1}$$

$$X_i = \begin{pmatrix} x_{1i} & z_{1i} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & x_{2i} & z_{2i} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & x_{3i} & z_{3i} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & x_{4i} & Y_{Fi} & T_i \end{pmatrix}_{4\times k} \text{ and } \theta = \begin{pmatrix} \beta_1 \\ \alpha_1 \\ \beta_2 \\ \alpha_2 \\ \beta_3 \\ \alpha_3 \\ \beta_4 \\ \delta \\ \eta \end{pmatrix}_{k\times 1},$$

where k is the total number of explanatory variables in all four equations. The system can be expressed then as

$$\begin{aligned} \tilde{y}_i^* &= X_i\theta + \varepsilon_i \\ \varepsilon_i &\sim N(0, \Sigma). \end{aligned}$$

The observations can then be stacked together as

$$\tilde{y}^* = X\theta + \varepsilon \quad \sim N\left(X\theta, I_n \otimes \Sigma\right)$$

where

$$\tilde{y}^* = \begin{pmatrix} \tilde{y}_1^* \\ \tilde{y}_2^* \\ \vdots \\ \tilde{y}_n^* \end{pmatrix}_{4n\times 1}, \quad \tilde{y} = \begin{pmatrix} \tilde{y}_1 \\ \tilde{y}_2 \\ \vdots \\ \tilde{y}_n \end{pmatrix}_{4n\times 1}, \quad X = \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{pmatrix}_{4n\times k}, e = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix}_{4n\times 1}.$$

For computational simplicity, I use data augmentation approach (Tanner and Wong, 1987; Albert and Chib, 1993) and treat the latent data $\tilde{y}^*$ as additional parameters of the model, thus making it a part of posterior. Using Bayes Theorem, the augmented posterior is given by

$$
\begin{aligned}
p\left(\tilde{y}^*,\theta,\Sigma \middle| \tilde{y}\right) &\propto p\left(\tilde{y} \middle| \tilde{y}^*,\theta,\Sigma\right) p\left(\tilde{y}^* \middle| \theta,\Sigma\right) p\left(\theta,\Sigma\right) \\
&\propto p\left(\theta,\Sigma\right) \prod_{i=1}^{n} p\left(\tilde{y}_i \middle| \tilde{y}_i^*\right) p\left(\tilde{y}_i^* \middle| \theta,\Sigma\right) \\
&\propto p\left(\theta,\Sigma\right) \prod_{i=1}^{n} \Big\{ \Big[I\left(F_i=1\right) I\left(F_i^*>0\right) + I\left(F_i=0\right) I\left(F_i^*\le 0\right) \Big] \times \\
&\qquad \Big[F_i \times I\left(Y_{Fi}=Y_{Fi}^*\right) + \left(1-F_i\right) I\left(Y_{Fi}=0\right) \Big] \times \\
&\qquad \Big[I\left(T_i=1\right) I\left(T_i^*>0\right) + I\left(T_i=0\right) I\left(T_i^*\le 0\right) \Big] \times \\
&\qquad \Big[Y_i \times I\left(Y_i=Y_i^*\right) + \left(1-Y_i\right) I\left(Y_i=0\right) \Big] \Big\} p\left(\tilde{y}^* \middle| \theta,\Sigma\right)
\end{aligned}
$$

where the second line follows from the assumed independence across individuals and I denotes an indicator function taking on the value one if the statement in the parenthesis is true, and is zero otherwise. Conditional on the parameters of the model, the augmented likelihood can be expressed as

$$
\begin{aligned}
p\left(\tilde{y}^* \middle| \theta,\Sigma\right) &= \left(2\pi\right)^{-\frac{4n}{2}} \left|I_n \otimes \Sigma\right|^{-\frac{1}{2}} \exp\left(-\frac{1}{2} \left(\tilde{y}^* - X\theta\right)' \left(I_n \otimes \Sigma\right)^{-1} \left(\tilde{y}^* - X\theta\right) \right) \\
&\propto \left(\left|I_n\right|^4 \left|\Sigma^n\right| \right)^{-\frac{1}{2}} \exp\left(-\frac{1}{2} \left(\tilde{y}^* - X\theta\right)' \left(I_n \otimes \Sigma\right)^{-1} \left(\tilde{y}^* - X\beta\right)\theta \right) \\
&\propto \left|\Sigma\right|^{-\frac{n}{2}} \exp\left(-\frac{1}{2} \sum_{i=1}^{n} e_i' \Sigma^{-1} e_i \right) \\
&\propto \left|\Sigma\right|^{-\frac{n}{2}} \exp\left(-\frac{1}{2} \sum_{i=1}^{n} \left(\tilde{y}_i^* - X_i\theta\right)' \Sigma^{-1} \left(\tilde{y}_i^* - X_i\theta\right) \right)
\end{aligned}
$$

I choose independent Normal prior distribution on θ:

$$\theta \sim N\left(\mu_{\theta_0}, V_{\theta_0}\right)$$

where μ_{θ_0} and V_{θ_0} denote the prior mean and covariance matrix of θ.

I place an Inverse Wishart distribution as a prior for covariance matrix Σ:

$$\Sigma^{-1} \sim W\left(a^{-1}, b\right),$$

where a is a positive definite matrix of size *4 × 4,* and b is a scalar.

3.4.2. Posterior Simulation

The conditional posteriors of both θ and Σ are proportional to the product of likelihood and the respective prior distribution. As shown in Appendix A, the conditional posterior for θ is also Normal:

$$p\left(\theta \middle| y^*, \Sigma\right) = N\left(\mu_{\theta_1}, V_{\theta_1}\right)$$

where

$$(3.4.2)\quad \begin{aligned} V_{\theta_1} &= \left(\sum_{i=1}^{n} X_i' \Sigma^{-1} X_i + V_{\theta_0}^{-1}\right)^{-1}, \\ \mu_{\theta_1} &= V_{\theta_1}\left(\sum_{i=1}^{n} X_i' \Sigma^{-1} y_i^* + V_{\theta_0}^{-1} \mu_{\theta_0}\right) \end{aligned}$$

and the conditional posterior distribution of Σ is Inverse Wishart:

$$(3.4.3)\quad \Sigma^{-1} \sim W\left(\left(\sum_{i=1}^{n}\left(\tilde{y}_i^* - X_i\theta\right)'\left(\tilde{y}_i^* - X_i\theta\right) + a\right)^{-1}, n+b\right).$$

Finally, the data augmentation step draws the values of latent variables T_i^*, Y_{Fi}^*, T_i^*, and Y_i^* conditional on the observed data $\tilde{y}_i$ and parameters of the model θ and Σ. The distributions of latent variables F_i^* and T_i^* are truncated normal:

$$\begin{aligned} F_i^* \middle| \theta, \Sigma, \tilde{y}_i &\sim TN_{R\left(F_i^*\right)}\left(\mu_{F^*}, \sigma_{F^*}^2\right) \\ T_i^* \middle| \theta, \Sigma, \tilde{y}_i &\sim TN_{R\left(T_i^*\right)}\left(\mu_{T^*}, \sigma_{T^*}^2\right) \end{aligned}$$

where $TN_R^*\left(\mu, \sigma^2\right)$ denotes normal distribution with mean μ and variance σ^2 truncated to the region R. For each individual i these distributions are truncated to the regions:

$$R\left(F_i^*\right) = \begin{cases} [0,\infty) & if\ F_i = 1 \\ (-\infty,0) & if\ F_i = 0 \end{cases}$$

and $$R\left(T_i^*\right) = \begin{cases} [0,\infty) & if\ T_i = 1 \\ (-\infty,0) & if\ T_i = 0 \end{cases}$$

I follow Geweke (1991) to draw values from these truncated normal distributions. I sample each latent index from a univariate truncated normal density conditional on the current values of other latent indices using the inverse distribution function method. The latent variables Y_{Fi}^* and Y_i^* are drawn only for those observations for which $F_i = 0$ and $Y_i = 0$, respectively. Y_{Fi}^* is drawn from the normal distribution:

$$Y_{Fi}^* \middle| \theta, \Sigma, \tilde{y}_i \sim N\left(\mu_{Y_F^*}, \sigma_{Y_F^*}^2\right),$$

and Y_i^* is drawn from the truncated normal distribution:

$$Y_i^* \middle| \theta, \Sigma, \tilde{y}_i \sim TN_{R\left(Y_i^*\right)}\left(\mu_{Y^*}, \sigma_{Y^*}^2\right)$$

where $$R\left(Y_i^*\right) = \begin{cases} [0,\infty) & if\ Y_i > 0 \\ (-\infty,0) & if\ Y_i = 0 \end{cases}$$

Again, I sample each latent index from a univariate normal density and univariate truncated normal density conditional on the current values of other latent indices using the inverse distribution function method. In case if $F_i = 1$ or $Y_i > 0$ then $Y_{Fi}^* = Y_{Fi}$ and $Y_i^* = Y_i$, respectively.

3.5. Data

The data used in this paper comes from the Agricultural Resource Management Survey (ARMS) data survey for the year 2001, conducted by the Economic Research Service (ERS) and the National Agricultural Statistics Service (NASS) of the U.S. Department of Agriculture (USDA). This survey provides field-level information on the financial condition, production practices, resource use, and the economic well-being of U.S. farm households. The data used in our analysis comes from two phases in the data collection process, phases II and III.

Phase II of the ARMS survey collects data associated with agricultural production practices, resource use, and variable costs of production for specific commodities and is conducted from September through December of the survey year. Phase III collects whole-farm finance variables, operator characteristics, and farm household information and is conducted from February through April, with the reference period being the previous year. Respondents sampled in Phase II are asked to complete a Phase III report. Data from both phases provide the link between agricultural resource use and farm financial conditions.

Farm operators included in the ARMS data are selected to ensure adequate coverage by state and region and to minimize reporting burden. Strata are based on state, the value of agricultural sales (farm size), and type of farm. NASS provides survey weights that account for these design features as well as for additional information available at the population level. Because of the complex design of the survey, all official estimates from the survey should be properly weighted. Therefore, NASS recommends the design-weighted approach as appropriate for many of the analyses for users of ARMS data (Panel to Review USDA's Agricultural Resource Management Survey, National Research Council, 2007). Ignoring the survey design can result in bias estimates, and make it impossible to perform statistically valid inferences. However, by including variables related to the design of the survey as predictor variables in a model results in a new, conditional model, for which the design is ignorable. In that case, model-based inference yields the appropriate conclusions for the sample, but not necessarily for the unweighted population. Therefore, to account for the survey design of the ARMS data, I included stratums in the set of explanatory variables. Particularly, state and farm size are included as predictive variables in the model.

ARMS data on corn production for 2001 includes data for 19 states. However, only four main corn producing states were chosen for analysis in the current chapter: Illinois, Indiana, Iowa, and Ohio.

Approximately 50% of all corn grown in the U.S. is from these four states. The resulting data set contains a total of 1726 observations.

3.5.1. Definitions of Variables

Table 3.1 provides a definition of variables used in estimation with indication as to which equation they were used in. Mean values and standard deviations of all variables are given in Table 3.2. The dependent variables include dummy variables reflecting farmer's decision on fall fertilizer application (which takes value of 1 if fall application was used and 0 otherwise), the nitrogen fertilizer application rates in fall measured in pounds per acre, tillage choice (takes value of 1 if conservation tillage was used and 0 otherwise), and the crop yield measured in bushels per acre.

Independent variables consist of farm and operator characteristics, cropping history, and soil quality determinants The set of variables governing the farmer's decision regarding fall fertilizer application is the same as the set used to explain the amount of nitrogen fertilizer applied in fall (though I allow the associated parameters to differ). For model parameters identification purposes it is necessary to include instrumental variables into equations related to farmer's decision making on fall fertilizer application and tillage choice.

The opportunity cost of labor is significantly higher during the late spring and growing season than during the fall (Huang, Hewitt, and Shank, 1998; Randall and Schmitt, 1998; Dinnes *et al*., 2002). The variable OFF-FARM represents number of days worked off farm. Working off-farm leaves less time to farmer to work in the field particularly during pre-planting and planting season when a lot of work should be done in a short period of time. It increases farmer's risk of not being able to finish everything on time and increases opportunity cost of time for farmer during planting season As a result, a farmer who works off-farm is hypothesized to apply fertilizer in the fall. Thus, I expect a positive sign for off-farm employment parameter in the fall fertilizer application equation. As for adoption of conservation tillage, off-farm employment is expected to be positively related to the adoption rate. Conservation tillage is found to either decrease crop yield or increase the variability in crop yield

(Beyaert, Schott, and White 2002; Al-Kaisi, Hanna, 2005; Halvorson *et al*., 2006). Since farmers working off-farm have more diversified sources of income, they fear yield losses or higher variability in yields less compared to those who are not employed off-farm. Thus, I expect a positive sign for off-farm employment parameter in tillage choice equation.

Operator characteristics include formal schooling. More educated farmers are more aware of negative environmental consequences of fall fertilizer application and conventional tillage so they are more likely to apply nitrogen in the spring rather than in the fall and choose conservation tillage. Education is assumed to affect yield, with more educated farmers assumed to have more knowledge that helps them to achieve higher yields. A discrete variable describes farmer's education and takes value of "1" if the farm operator had some college education and "0". Total acreage operated by the farmer was included as an indicator of size of operation. The bigger is the farm the more time it requires to complete a series of machinery operations, such as tillage, fertilizer application, and planting. Therefore, I expect positive signs for total acreage parameter in the fall fertilizer application and tillage choice equations.

The amount of fertilizer is typically determined after "credit" is given to the amount of nutrients available from the soil, the previous legume crop, and livestock manure. Once the needed amount of fertilizer is estimated, management decisions can be made about the fertilizer application method and timing. Therefore, dummy variables for whether the field received manure and whether corn was rotated with a legume crop are included in the model. Giving appropriate nitrogen credits to rotating corn with legume crop and animal manure applications is recommended to avoid overapplication of fertilizer nitrogen. Therefore, farmers who apply manure and rotate corn with legume crops are expected to reduce amount of nitrogen applied and, consequently, have lower probability of fall fertilizer application.

To capture the yield differences among fields and farms, the variable "Land Capability Class" was used. The Land Capability Classification indicates the suitability of soils for most kinds of field crops. Land is evaluated on the basis of the range of potential crops, productivity, ease of management and risk of degradation. Capability classes are designated by the numbers 1 through 8. The numbers indicate progressively greater limitations and narrower choices for practical use. A dummy variable was created that takes the value of one if the capability class is 1 or 2, and is zero otherwise. I expect farmers to use more of nitrogen on the land with higher productivity as marginal return on nitrogen will be higher on that land.

The number of days available to complete fertilizer application is also an important consideration in deciding on the timing of fertilizer application (Iowa State University Extension, 2007a; Rotz and Harrigan, 2004; Dillon, 1999). States report the number of days each week that soil and moisture conditions are suitable for fieldwork. These data also captures climatic and weather differences among sites that affect farmers' decision making regarding the timing of fertilizer application (Fletcher and Featherstone, 1987; Feinerman, Choi, and Johnson, 1990; Kurkalova, Kling, and Zhao, 2006; Wu *et al.*, 2004). Estimates of the number of suitable fieldwork days are based on weekly records. The spring data covers the usual corn planting dates of mid-April to mid-May. The fall data covers the period of mid-September to the end of October. Climatic variables also found to affect choice of tillage and yield (Kurkalova, Kling, and Zhao, 2006; Uri, 1998). Hence, the number of suitable fieldwork days in spring is used as an explanatory variable in tillage and yield equations.

Slope of a field is added as an independent variable in tillage equation as it is found to affect a choice of tillage system (Kurkalova, Kling, and Zhao, 2006; Wu *et al.,* 2004; Wu and Babcock, 1998; Uri, 1998). Land slope represents the amount of inclination of the soil surface from the horizontal expressed as the vertical distance divided by the horizontal distance. The higher the slope the bigger the chance of soil erosion when it is used for crop production. As a result, I expect a positive sign for the slope parameter in the tillage equation. Ownership of a land is also found to affect choice of tillage (Kurkalova, Kling, and Zhao, 2006; Wu and Babcock, 1998; Soule, Tegene, and Wiebe, 2000; Lichtenberg, 2007) and, therefore, is included as an explanatory variable in tillage equation. Finally, to capture the differences across the states that are not reflected by the independent variables, state dummies are introduced into each equation of the model.

3.6. Results

For each of the specifications, 25,000 draws from the posterior distribution were obtained. The first 5,000 were discarded as a burn-in, and the remaining 20,000 were used for analysis. Posterior means, standard deviations, and probabilities of being positive for each of the parameters of interest are given in Table 3.3a, 3.3b and 3.3c.

Several important results emerge from Tables 3a, 3b, and 3c. First, the posterior means and standard deviations on the off-farm employment variable suggest that the opportunity cost of farmers' time in spring plays a significant role in their decision-making regarding timing of fertilizer application and tillage choice. Working off –farm leaves farmers with fewer days for field work during planting season so farmers who work off-farm have a higher probability of fall fertilizer application than those who are not employed off- farm. Off-farm employment is also found to affect the adoption of conservation tillage. This result is consistent with previous findings by Kurkalova, Kling, and Zhao (2006) and Fuglie (1999) who found a higher adoption of conservation tillage by farmers working off-farm. Second, the amount of fertilizer applied in fall was found to be crucial for crop yield. This indicated in Table 3.3b by the largely positive posterior distribution (i.e., high values for $\Pr\left(\cdot > 0 \mid y\right)$) for the parameter associated with fall nitrogen application in yield equation. It appears that, all else equal, farmers who apply higher rate of nitrogen in fall have higher yields. Third, decisions on the timing of fertilizer application and tillage choice are interrelated. Conservation tillage is associated with the fall fertilizer application, the fact is indicated in Table 3.3c by the largely positive posterior distribution for the correlation coefficients between decisions on whether to apply in fall and amount of application fall nitrogen application, and tillage choice.

Other variables included in the model also generally perform as expected. The manure and rotation variables affect both whether and how much nitrogen to apply in fall. Specifically, manure application and crop rotation tend to decrease probability of fall application and reduce the amount of nitrogen applied. Manure coefficient is negative (with $\Pr\left(\cdot > 0 \mid y\right)$ = 0.12) suggesting that farmers applying manure apply less of fertilizer. Rotation with a legume crop is also found to reduce the total nitrogen applied, a result that is consistent with Wu and Babcock (1998). At the same time, manure and rotation were not found to affect the adoption of conservation tillage.

Field acreage and fieldwork days are also found to affect farmers' decisions regarding nitrogen application and choice of tillage practice. Larger farms, requiring more time to finish planting and fertilizing in the spring are more likely to employ fall fertilizer and choose conservation tillage. Additional work days during the fall are found to increase the probability of fall fertilizer applications and the amount of fertilizer applied. At the same time, additional work days during the spring are negatively correlated with adoption of conservation tillage. This result is consistent with agronomic science: the higher precipitation (less additional work days during the spring) limits crop production.

College education has positive effect on adoption of conservation tillage. Similar results were obtained by Wu and Babcock (1998), Korsching *et al.* (1983). However, college education was found not to affect timing of fertilizer application and yield.

The performance of soil characteristics is generally consistent with agronomic information. Lands with a high land capability are found to increasingly rely upon fertilizer in the fall and are more likely to use conservation tillage. This result supports the importance of land quality in the choice of farming practice (Lichtenberg, 2004; Kurkalova, Kling, and Zhao, 2006; Wu and Babcock, 1998; Soule, Tegene, and Wiebe, 2000).

Slope is found to affect the adoption of conservation tillage. Conservation tillage occurs more frequently on sloped land since it helps to reduce soil losses due to soil erosion. The positive relationship between the slope and the probability of conservation tillage adoption is consistent with results of previous studies by Wu and Babcock (1998), Kurkalova, Kling, and Zhao (2006), and Uri (1998).

Tenancy is found to affect the adoption of conservation tillage. Conservation tillage is more frequently adopted by owners of the land. This result supports previous findings by Soule, Tegene, and Wiebe (2000), Lichtenberg (2007), Wu and Babcock (1998), and Wu *et al*. (2004).

3.7. Environmental Implications

In this section, I consider the implications of estimated model, both in terms of the appropriate credits for rotation and manure use and in terms of the potential impacts of policies to reduce the nitrogen use.

3.7.1. Rotation and manure credits

The agronomic fertilizer recommendations indicate that nitrogen application rates should be adjusted to account for nitrogen supplied by previous legume crops and manure application (USDA, ERS, 2001). When managed correctly, nutrients from previous legume crops and in livestock manure can be a valuable resource of nitrogen. Therefore, crediting for rotation and manure nutrients can be an important factor in deciding nitrogen application rates (Blackmer, 2000; Sharpley *et al*., 1998). If farmers do not credit these sources of nitrogen, they may end up applying more nitrogen than is agronomically necessary. To examine this issue, the estimation results are used in this subsection to compute the amount of rotation and manure credits by farmers in the fall.

3.7.1.1. Calculation Details

The rotation nitrogen credit refers to the difference between the amount of nitrogen applied for continuous corn and nitrogen applied for corn following soybean all else equal. Likewise, the manure nitrogen credit refers to the difference between the amount of nitrogen applied without manure application and nitrogen applied with manure application.

The estimated model is used to estimate the distributions of implied credits being used for rotation and applied manure. Specifically, the rotation credit is given by $\Delta_i^r = Y_{1i}^r - Y_{0i}^r$, where Y_{1i}^r corresponds to amount of nitrogen applied for a corn-corn rotation and Y_{0i}^r corresponds to amount of nitrogen applied for corn-soybean rotation. Similarly, the manure credit is given by $\Delta_i^m = Y_{1i}^m - Y_{0i}^m$, where Y_{1i}^{m} corresponds to amount of nitrogen applied with manure not applied and Y_{0i}^{m} corresponds to amount of nitrogen applied with manure applied.

Literature on the treatment effect focuses primarily on methods for estimating various average returns to the receipt of treatment. Particularly, it focuses on: (1) the average treatment effect (ATE), and (2) the effect of treatment on treated (TT) (Li, Poirier, and Tobias, 2004; Tobias, 2006).

For the current research, ATE is defined as the expected nitrogen credit for rotation and manure by a randomly chosen farmer. Formally,

$$ATE(X) \equiv E(\Delta | X) = E(Y_1 - Y_0 | X).$$

A conceptually different parameter is the credit by farmers who actually used fall fertilizer applications. In this case Δ represents the average credit for rotation and manure by farmers who actually used fall fertilizer application and is referred to in the literature as the Treatment on the Treated (TT). Formally,

$$TT(X, F=1) \equiv E(\Delta | X, F=1) = E(Y_1 - Y_0 | X, F=1).$$

Given notation and assuming that covariates x_i are known, I characterize the following out-of-sample sampling distributions, given θ and x_i, as follows:

(3.7.1) $p(\Delta | \theta, x_i)$

(3.7.2) $p(\Delta | \theta, x_i, F_i = 1)$.

The first density in (3.7.1) gives the distribution of nitrogen credit for the farmer selected at random, whereas the density in (3.7.2) gives the nitrogen credit for those farmers who actually used fall fertilizer application.

Expressions (3.7.1) and (3.7.2) for ATE and TT predictive distributions are conditioned on the parameters θ. A proper Bayesian approach to characterize the posterior predictive distributions of the nitrogen credit is to integrate out the parameters θ from the densities (3.7.1) and (3.7.2) by averaging them over the posterior distribution of those parameters. Formally,

$$(ATE): \quad p\left(\Delta \middle| x_i, Data\right) = \int_{\theta} p\left(\Delta \middle| \theta, x_i, Data\right) p\left(\theta \middle| Data\right) d\theta$$

$$(TT\ ): \quad p\left(\Delta \middle| x_i, F_i = 1, Data\right) = \int_{\theta} p\left(\Delta \middle| x_i, \theta, F_i = 1, Data\right) p\left(\theta \middle| Data\right) d\theta\,,$$

To calculate these predictives I use the following approximations (Poirier and Tobias, 2003; Tobias, 2006):

$$(ATE): \quad \hat{p}\left(\Delta \middle| x_i, Data\right) = \frac{1}{K}\sum_{k=1}^{K} p\left(\Delta \middle| x_i, \theta = \theta^k, Data\right),$$

and $$(TT): \quad \hat{p}\left(\Delta \middle| x_i, F_i = 1, Data\right) = \frac{1}{K}\sum_{k=1}^{K} p\left(\Delta \middle| x_i, \theta = \theta^k, F_i = 1, Data\right),$$

where θ^k denotes draws from the posterior distribution of θ and K denotes number of such parameter draws.

3.7.1.2. Results

There are several guides provided by University Extensions illustrating how to estimate the crop available nutrients from previous legume crops and manure application (University of Nebraska-Lincoln Extension, 2006; Iowa State University Extension, 2003, 2007b). According to these guides, the nitrogen credit given for soybeans should be 40-50 lb/acre. The amount of the total nitrogen available from manure depends on the species and whether the manure is liquid or solid. The recommended manure credits for average manure application rates in Illinois, Indiana, Iowa, and Ohio in year 2001 were 110-130 lb/acre.

Two types of distributions for manure and rotation credits were constructed: (1) the farmer's expected credit in fall independently on his/her timing of fertilizer application (ATE) and (2) credit by farmers who actually used fall fertilizer application (TT). The TT predictive is shifted to the right relative to ATE, indicating that both manure and rotation credits are much higher for those farmers who actually use fall nitrogen application. Specifically, figures 3.1 and 3.2 present the ATE and TT posterior predictive distributions of rotation credits for fall applied nitrogen. The TT predictive is shifted to the right compared to ATE distribution and, consequently, has higher mean and median values.

Figure 3.1. Rotation Credit for Fall Application ATE

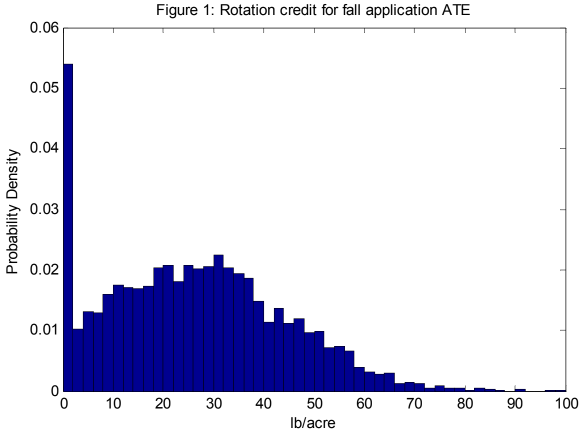
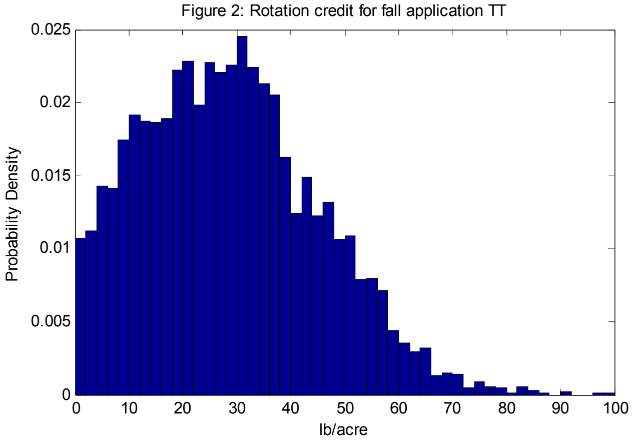


Figure 3.2. Rotation Credit for Fall Application TT



The posterior mean of TT for rotation credit calculated for ARMS 2001 data is 29.35 lb/acre for fall suggesting that on average farmers who applied fertilizer in fall used 29.35 lb/acre more of nitrogen for continuous corn than for corn following soybean. This value is lower than the level of rotation credit that farmers are recommended by Extension: 40-50 lb/acre.

Previous attempts to quantify the soybean nitrogen credit showed that it varied with year and soil characteristics. Gentry *et al.* (2001) obtained the value of 27 kg/ha $\left(\approx 30.3\ lb/acre\right)$ of nitrogen credit in Illinois. In the research of Bundy, Andraski, and Wolkowski (1993) estimated nitrogen credits that differed significantly among locations and years and ranged from 22 to 210 kg/ha $\left(\approx 24.7\text{-}317.7\ lb/acre\right)$. Such a big discrepancy in the value of nitrogen credit suggests that there is a high uncertainty about amount of nitrogen available for plant growth from previous legume crop. As a result, farmers credit less nitrogen than is recommended and apply more nitrogen to reduce risk of yield losses associated with nitrogen deficiency.

The posterior probability that on average farmers who apply fertilizer in fall credit at least 50 lb/acre of nitrogen for rotation is also calculated:

$$\Pr\left(\Delta > 50 \middle| x = \bar{x}, F_i = 1, Data\right) = 0.25$$

This result says that on average 75 percent of farmers who apply fertilizer in the fall do not follow recommendations and credit less than 50 lb/acre of nitrogen for rotation.

Analogous results are obtained for manure credits. Figure 3.3 presents TT posterior predictive for manure credit in the fall. The posterior means of TT for manure credit calculated for ARMS 2001 data is 46.93 lb/acre for fall. Again, this value is lower than the level of manure credit that is recommended to farmers by university extensions: 110-130 lb/acre.

3.3. Manure Credit for Fall Application

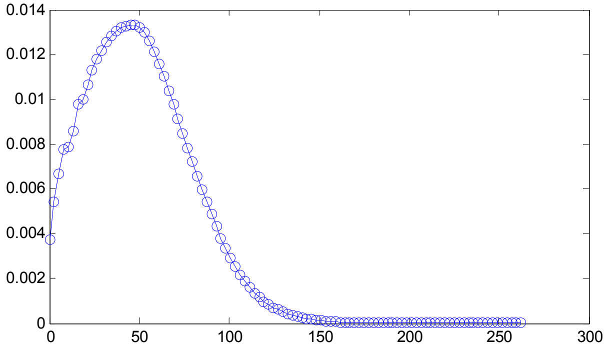


Figure 3: Manure credit TT for fall application

The posterior probability that on average farmers who apply fertilizer in fall credit at least 100 lb/acre of nitrogen for manure application is also calculated:

$$\Pr\left(\Delta > 100 \middle| x = \bar{x}, F_i = 1, Data\right) = 0.07$$

This result says that on average 93 percent of farmers who apply fertilizer in fall do not follow recommendations and credit less than 100 lb/acre of nitrogen for manure application.

University of Minnesota Extension (2008) calculated that, on average, manure nitrogen would be approximately 75 pounds per manured corn acre for typical small dairies farm in southeastern Minnesota. The findings here are consistent with their estimates.

Results for both rotation and manure credits suggest that applying nitrogen in spring increases the level of credit. Therefore, policy to switching from fall to spring fertilizer application will reduce amount of fertilizer applied since farmers credit more for manure and rotation.

3.7.2. Demand for Nitrogen Fertilizer

One way of reducing nitrogen application in corn production is imposing tax on the nitrogen. This paper examines the potential implications of adopting a tax strategy as the policy choice to reduce the level of nitrogen application. There are several studies that focused primarily on estimating the fertilizer demand and corresponding fertilizer price elasticities (Griliches, 1958 and 1959; Roberts and Heady, 1982; Roberts, 1986; Vroomen and Larson, 1991; Denbaly and Vroomen, 1993). Some other studies investigated the effect of agro-environmental policies on agricultural production and fertilizer input demand (Onianwa *et al*., 1992; Abler and Shortle, 1995, Hertel and Stiegert, 2000; Hertel, Stiegert, and Vroomen, 1996).

Vroomen and Larson (1991) obtained estimates of -0.23 as the minimum and -0.85 as the maximum own-price elasticity of demand for nitrogen in the Corn Belt area. Similarly, in their study of nutrient plant elasticities of demand for corn production in the United States, Denbaly and Vroomen (1993) obtained estimates of -0.23 for the short-run and -0.48 for the long-run price elasticities of demand for nitrogen in corn production. Onianwa *et al.* (1992) estimated elasticity of demand for nitrogen in corn production in Minnesota to be -0.35. Hertel and Stiegert (2000) obtained the estimate of -0.227 for own-price elasticity of demand for nitrogen in corn production in Indiana.

The calculation of the elasticity of demand for sample selection models is different from the regular linear models (Yen, 2005). If the probability of a positive observation for each dependent variable y_i is $P\left(y_i > 0\right) = \Phi\left(z'\alpha_i\right)$, with the observed $y_i = x'\beta_i$, and $y_i = 0$ otherwise, then the elasticity of unconditional mean with respect to x_j is

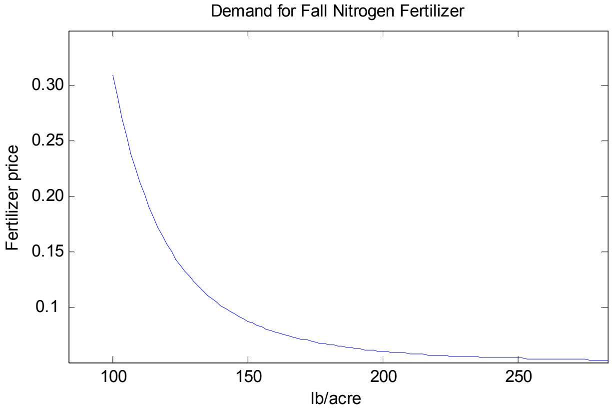
$$e_i^u = \left\{ \frac{\beta_{ij}}{x'\beta_{ij}} + \lambda\left(z'\alpha_i + \rho_{ii}^{vu}\sigma_i\right)\alpha_{ij} \right\} x_j \text{ where } \lambda = \frac{\phi(\cdot)}{\Phi(\cdot)},$$

and the elasticity of conditional mean with respect to x_j is

$$e_i^c = \left\{ \frac{\beta_{ij}}{x'\beta_{ij}} + \left[\lambda\left(z'\alpha_i + \rho_{ii}^{vu}\sigma_i\right) - \lambda\left(z'\alpha_i\right)\right]\alpha_{ij} \right\} x_j .$$

Figure 3.4 shows demand for nitrogen in fall. As expected, the higher the price of fall applied nitrogen, the less is demand for nitrogen in fall. The elasticity of the conditional mean of demand for fall applied nitrogen using the ARMS 2001 data is calculated to be $e^c = -0.58$.

3.4. Demand for Fall Nitrogen Fertilizer



This result shows that the 10 percent tax imposed on fall nitrogen will reduce the total amount of nitrogen applied by 5.8 percent. These result supports previous findings by Vroomen and Larson

(1991), Denbaly and Vroomen (1993), Onianwa *et al*. (1992), Hertel, Stiegert, and Vroomen (2000) who obtained low estimates for own-price elasticity of demand for nitrogen in corn production.

Control of nonpoint source pollution often requires regulation of inputs. Wu and Tanaka (2005) found that fertilizer-tax is much more cost effective than other easement policies (incentive payments for conservation tillage, for corn-soybeans rotations, and for cropland retirement) and advocated its use for reducing nitrogen loads from Upper Mississippi River Basin to the Gulf of Mexico. Estimated elasticity in this chapter indicates that a tax on nitrogen fertilizer would reduce nitrogen fertilizer use in corn production. However, effectiveness of a tax in reducing nitrogen fertilizer use is limited due to elasticity being less than one.

Tax imposed on nitrogen fertilizer in fall reduces amount of fertilizer applied in the fall. As a result, it might affect crop yields. Let Σ_{-ij} denote the variance-covariance matrix Σ with row i and column j removed, σ_{-i} denote the i^{th} column of the variance-covariance matrix Σ with i^{th} element removed, and, finally, ε_{-i} denote the error vector with the i^{th} element removed. The posterior predictive of crop yield, conditional on model parameters, θ, Σ, and farmer's decision on fall nitrogen application, is given by:

$$
\begin{aligned}
P\left(Y_i^* \middle| F_i = 1, \theta, \Sigma\right) &= P\left(Y_i^* \middle| F_i^* > 0, \theta, \Sigma\right) \\
&= \left[P\left(F_i^* > 0 \middle| \theta, \Sigma\right)\right]^{-1} \int_0^\infty P\left(Y_i^*, F_i^* \middle| \theta, \Sigma\right) dF_i^* \\
&= \left[P\left(F_i^* > 0 \middle| \theta, \Sigma\right)\right]^{-1} P\left(Y_i^* \mid \theta, \Sigma\right) P\left(F_i^* \middle| Y_i^*, \theta, \Sigma\right)
\end{aligned}
$$

$$
P\left(F_i^* \middle| T_i^*, \theta, \Sigma\right) = \Phi\left(x_i\beta_1^1 + z_{1i}\alpha_1^1 + \sigma_{-1}^1{}' \left(\Sigma_{-11}^1\right)^{-1} \varepsilon_{-1}\,, \quad \left(\sigma_1^2\right)^1 - \sigma_{-1}^1{}' \left(\Sigma_{-11}^1\right)^{-1} \sigma_{-1}^1\right)
$$

$$
P\left(Y_i^* \mid \theta, \Sigma\right) = \phi\left(x_{4i}\beta_4 + \delta Y_{Fi} + \eta T_i + \begin{pmatrix} \sigma_{24} \\ \sigma_{34} \end{pmatrix}' \begin{pmatrix} \sigma_2^2 & \sigma_{23} \\ \sigma_{23} & \sigma_4^2 \end{pmatrix}^{-1} \begin{pmatrix} e_{2i} \\ e_{3i} \end{pmatrix}, \sigma_4^2 - \begin{pmatrix} \sigma_{24} \\ \sigma_{34} \end{pmatrix}' \begin{pmatrix} \sigma_2^2 & \sigma_{23} \\ \sigma_{23} & \sigma_4^2 \end{pmatrix}^{-1} \begin{pmatrix} \sigma_{24} \\ \sigma_{34} \end{pmatrix} \right)
$$

$$P\left(F_i^* \mid \theta,\Sigma\right)=\Phi\left(x_{1i}\beta_1+z_{1i}\alpha_1+\begin{pmatrix}\sigma_{12}\\ \sigma_{14}\end{pmatrix}'\begin{pmatrix}\sigma_2^2 & \sigma_{24}\\ \sigma_{24} & \sigma_4^2\end{pmatrix}^{-1}\begin{pmatrix}e_{2i}\\ e_{4i}\end{pmatrix},\ \sigma_1^2-\begin{pmatrix}\sigma_{12}\\ \sigma_{14}\end{pmatrix}'\begin{pmatrix}\sigma_2^2 & \sigma_{24}\\ \sigma_{24} & \sigma_4^2\end{pmatrix}^{-1}\begin{pmatrix}\sigma_{12}\\ \sigma_{14}\end{pmatrix}\right)$$

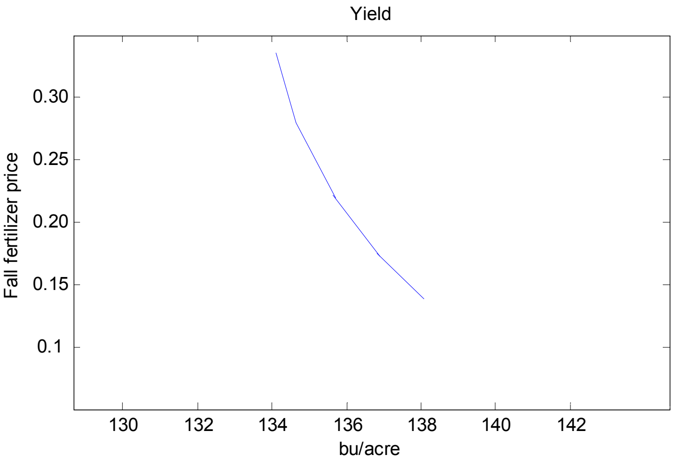
Since this conditional predictive has above closed-form solution, the unconditional (on the parameters θ) predictive can be obtained via “Rao-Blackwellization” (Li, Poirier, and Tobias, 2004; Tobias, 2006) by averaging draws from the following distribution:

$$\begin{aligned}E\left(Y_i^*\middle|x_i,F_i=1,Data\right)&=\int_\theta p\left(Y_i^*\middle|x_i,\theta,F_i=1,Data\right)p\left(\theta\middle|Data\right)d\theta\\ &=\frac{1}{K}\sum_{k=1}^{K}p\left(Y_i^*\middle|x_i,\theta=\theta^k,F_i=1,Data\right),\end{aligned}$$

where K denotes number of draws of parameters.

Figure 3.5 shows the effect of tax imposed on fall applied nitrogen on the crop yield. Results show that tax imposed on fall nitrogen fertilizer lowers crop yields. Moreover, as a result of 100 percent tax on fall applied nitrogen yields are reduced by almost 4 bu/acre.

3.5. Yield



3.8. Conclusion

Fall fertilizer application is associated with excessive application of nitrogen and higher amount of lost nitrogen due to leaching, runoff, and denitrification. All this makes spring nitrogen application more desirable from environmental point of view. As was shown in the previous chapter, tax imposed on fall applied nitrogen reduces amount of nitrogen fertilizer applied in the fall. Moreover, it induces some farmers to switch from fall to spring application. As a result, tax imposed on fall applied nitrogen, works as a tool in reducing the amount of nitrogen leached from fields to water resources. However, reduced amount of nitrogen fertilizer applied might have an adverse effect on a crop yield. As a result, farmers might be at a risk of losses. Another factor that affects crop yield is a choice of tillage system that in turn has effect on timing of fertilizer application. This chapter proposes a model that accounts for the relationship between fall fertilizer application and choice of tillage system, and examines the implications of adopting these two practices on nitrogen productivity, which is measured by crop yield. Results show that tax imposed on fall nitrogen fertilizer lowers crop yields. However, as a result of 100 percent tax on fall applied nitrogen yields are reduced by about 4 bu/acre. Furthermore, the results also show that conservation tillage is associated with the fall fertilizer application.

Agronomists have long recommended that nitrogen application rates should be adjusted to account for nitrogen supplied by previous legume crops and manure. If farmers do not credit other sources of nitrogen, they may apply more nitrogen than can be used by crop and increase the amount of nitrogen leaving the field. Results of this research show that, on average, farmers credit less nitrogen available from manure and previous legume crops than is recommended by University Extension.

Appendices:

Appendix 1: Conditional posterior distribution

Using the augmented posterior from section 3.1, the conditional posterior for the parameter vector θ is given by:

$$\begin{aligned}
p\left(\theta \middle| \tilde{y}^*,\Sigma\right) &\propto \exp\left(-\frac{1}{2}\left[\sum_{i=1}^{n}\left(\tilde{y}_i^* - X_i\theta\right)'\Sigma^{-1}\left(\tilde{y}_i^* - X_i\theta\right) + \left(\theta-\mu_{\theta_0}\right)' V_{\theta_0}'\left(\theta-\mu_{\theta_0}\right)\right]\right) \\
&\propto \exp\Bigg(-\frac{1}{2}\Bigg[\sum_{i=1}^{n}\left(\tilde{y}_i^{*\prime}\Sigma^{-1}\tilde{y}_i^* - 2\theta' X_i'\Sigma^{-1}\tilde{y}_i^* + \theta' X_i'\Sigma^{-1}X_i\theta\right) \\
&\qquad + \left(\theta' V_{\theta_0}^{-1}\theta - 2\theta' V_{\theta_0}^{-1}\mu_{\theta_0} + \mu_{\theta_0}' V_{\theta_0}^{-1}\mu_{\theta_0}\right) \\
&\propto \exp\left(-\frac{1}{2}\left[\theta'\left(\sum_{i=1}^{n} X_i'\Sigma^{-1}X_i + V_{\theta_0}^{-1}\right)\theta - 2\theta'\left(\sum_{i=1}^{n} X_i'\Sigma^{-1}\tilde{y}_i^* + V_{\theta_0}^{-1}\mu_{\theta_0}\right)\right]\right) \\
&\propto \exp\left(-\frac{1}{2}\left[\theta' V_{\theta_1}^{-1}\theta - 2\theta' V_{\theta_1}^{-1}\mu_{\theta_1}\right]\right) \\
&\propto \exp\left(-\frac{1}{2}\left[\theta' V_{\theta_1}^{-1}\theta - 2\theta' V_{\theta_1}^{-1}\mu_{\theta_1} + \mu_{\theta_1}' V_{\theta_1}^{-1}\mu_{\theta_1} - \mu_{\theta_1}' V_{\theta_1}^{-1}\mu_{\theta_1}\right]\right) \\
&\propto \exp\left(-\frac{1}{2}\left[\left(\theta-\mu_{\theta_1}\right)' V_{\theta_1}^{-1}\left(\theta-\mu_{\theta_1}\right)\right]\right)
\end{aligned}$$

where $V_{\theta_1} = \left(\sum_{i=1}^{n} X_i'\Sigma^{-1}X_i + V_{\theta_0}^{-1}\right)^{-1}$ and $\mu_{\theta_1} = V_{\theta_1}\left(\sum_{i=1}^{n} X_i'\Sigma^{-1}y_i^* + V_{\theta_0}^{-1}\mu_{\theta_0}\right)$

Therefore,

$$p\left(\theta \middle| y^*,\Sigma\right) = N\left(\mu_{\theta_1}, V_{\theta_1}\right)$$

The conditional posterior for $\Sigma \middle| \theta, \tilde{y}^*$ is similarly derived from the augmented posterior,

$$\begin{aligned}
p\left(\Sigma \middle| \tilde{y}^*,\theta\right) &\propto |\Sigma|^{-n/2}\exp\left(-\frac{1}{2}\sum_{i=1}^{n}\left(\tilde{y}_i^* - X_i\theta\right)'\Sigma^{-1}\left(\tilde{y}_i^* - X_i\theta\right)\right) \\
&\quad \times |\Sigma|^{-(b+n+1)/2}\exp\left(-tr\left(a\Sigma\right)^{-1}/2\right) \\
&\propto |\Sigma|^{-(b+2n+1)/2}\exp\left(-\frac{1}{2}\left[\sum_{i=1}^{n} tr\left(\tilde{y}_i^* - X_i\theta\right)\left(\tilde{y}_i^* - X_i\theta\right)'\Sigma^{-1} + tr\left(a\Sigma\right)^{-1}\right]\right)
\end{aligned}$$

$$\propto \left|\Sigma\right|^{-(b+2n+1)/2} \exp\left(-\frac{1}{2} tr\left(\left[\sum_{i=1}^{n} \left(\tilde{y}_i^* - X_i\theta\right)\left(\tilde{y}_i^* - X_i\theta\right)' + a^{-1} \right] \Sigma^{-1} \right) \right)$$

Therefore,

$$\Sigma^{-1} \left| \tilde{y}_i^*, \theta \sim W\left(\left(\sum_{i=1}^{n} \left(\tilde{y}_i^* - X_i\theta\right)' \left(\tilde{y}_i^* - X_i\theta\right) + a \right)^{-1}, n+b \right) \right.$$

Appendix 2: **The posterior simulator**

The posterior simulator employs a Gibbs sampling procedure, drawing in turn from the conditional posterior distribution for $\theta, \Sigma,$ and $\tilde{y}^*$:

Step 0: Set $\left(\tilde{y}_i^*\right)^0 = \left[\left(F_i^*\right)^0 \left(Y_{Fi}^*\right)^0 \left(T_i^*\right)^0 \left(Y_i^*\right)^0 \right]' = \left[F_i \;\; Y_{Fi} \;\; S_i \;\; Y_i \right]'$ and $\Sigma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$.

Step 1: Draw θ^1 from the distribution given by (3.4.2) conditional on $\left(\tilde{y}_i^*\right)^0$ and Σ^0.

Step 2: Draw the elements of the covariance matrix Σ^1 conditional on θ^1 and $\left(\tilde{y}_i^*\right)^0$ using (3.4.3).

Step 3: Data augmentation step. Draw the latent data $\left(\tilde{y}_i^*\right)^1 = \left[\left(F_i^*\right)^1 \left(Y_{Fi}^*\right)^1 \left(T_i^*\right)^1 \left(Y_i^*\right)^1 \right]'$ conditional on θ^1 and Σ^1:

j. Compute the errors ε_{2i}, ε_{3i} and ε_{4i} given θ^1 from *Step 1* and latent data $\left(Y_{Fi}^*\right)^0$, $\left(T_i^*\right)^0$, and $\left(Y_i^*\right)^0$;

k. Draw $\left(F_i^*\right)^1$ from

$$TN_{[0,\infty)}\left(x_i\beta_1^1 + z_{1i}\alpha_1^1 + \sigma_{-1}^{1}{}'\left(\Sigma_{-11}^1\right)^{-1} \varepsilon_{-1}, \;\; \left(\sigma_1^2\right)^1 - \sigma_{-1}^{1}{}'\left(\Sigma_{-11}^1\right)^{-1} \sigma_{-1}^1 \right) \text{ if } F_i \geq 0$$

where Σ_{-ij} denotes the variance-covariance matrix Σ with row i and column j removed, σ_{-i} denotes the i^{th} column of the variance-covariance matrix Σ with i^{th} element removed, and, finally, ε_{-i} denotes the error vector with the i^{th} element removed, and

$$TN_{(-\infty,0]}\left(x_i\beta_1^1 + z_{1i}\alpha_1^1 + \sigma_{-1}^{1\prime}\left(\Sigma_{-11}^1\right)^{-1}\varepsilon_{-1},\quad \left(\sigma_1^2\right)^1 - \sigma_{-1}^{1\prime}\left(\Sigma_{-11}^1\right)^{-1}\sigma_{-1}^1\right) \quad \text{if } F_i < 0$$

l. Compute the errors ε_{1i} given θ^1 from *Step 1* and latent data $\left(F_i^*\right)^1$;

m. Draw $\left(Y_{Fi}^*\right)^1$ from

$$N\left(x_{2i}\beta_2^1 + z_{2i}\alpha_2^1 + \sigma_{-2}^{1\prime}\left(\Sigma_{-22}^1\right)^{-1}\varepsilon_{-2}^1,\quad \left(\sigma_2^2\right)^1 - \sigma_{-2}^{1\prime}\left(\Sigma_{-22}^1\right)^{-1}\sigma_{-2}^1\right) \qquad \text{if } \left(F_i^*\right)^1 < 0$$

and set $Y_{Fi}^* = Y_{Fi}$ if $\left(F_i^*\right)^1 \geq 0$

n. Compute the errors ε_{2i} given θ^1 from *Step 1* and latent data $\left(Y_{Fi}^*\right)^1$;

o. Draw $\left(T_i^*\right)^1$ from

$$TN_{[0,\infty)}\left(x_{3i}\beta_3^1 + \delta_3^1 Y_{Fi}^1 + \sigma_{-3}^{1\prime}\left(\Sigma_{-33}^1\right)^{-1}\varepsilon_{-3}^1,\quad \left(\sigma_3^2\right)^1 - \sigma_{-3}^{1\prime}\left(\Sigma_{-33}^1\right)^{-1}\sigma_{-3}^1\right) \quad \text{if } T_i \geq 0$$

$$TN_{(-\infty,0]}\left(x_{3i}\beta_3^1 + \delta_3^1 Y_{Fi}^1 + \sigma_{-3}^{1\prime}\left(\Sigma_{-33}^1\right)^{-1}\varepsilon_{-3}^1,\quad \left(\sigma_3^2\right)^1 - \sigma_{-3}^{1\prime}\left(\Sigma_{-33}^1\right)^{-1}\sigma_{-3}^1\right) \quad \text{if } T_i < 0$$

p. Compute the errors ε_{3i} given θ^1 from *Step 1* and latent data $\left(T_i^*\right)^1$;

q. Draw $\left(Y_i^*\right)^1$ from

$$TN_{(-\infty,0]}\left(x_{4i}\beta_4^1 + \delta_4^1 Y_{Fi}^1 + \sigma_{-4}^{1\prime}\left(\Sigma_{-44}^1\right)^{-1}\varepsilon_{-4}^1,\quad \left(\sigma_4^2\right)^1 - \sigma_{-4}^{1\prime}\left(\Sigma_{-44}^1\right)^{-1}\sigma_{-4}^1\right) \quad \text{if } \left(Y_i\right)^1 < 0$$

and set $Y_i^* = Y_i$ if $\left(Y_i\right)^1 \geq 0$.

r. Compute the errors ε_{4i} given θ^1 from *Step 1* and latent data $\left(Y_i^*\right)^1$, $\left(T_i^*\right)^1$, and $\left(Y_{Fi}^*\right)^1$;

Step 4: Repeat steps 1-3 K times.

The Gibbs algorithm generates a sample of size K from conditional posterior distribution of each of the parameters of the model. The first K_0 draws are discarded as burn-in, the remaining $K_1 = K - K_0$ draws are used for the analysis.

References

[1] Abler, D. G., James S. Shortle. “Technology as an Agricultural Pollution Control Policy”. *American Journal of Agricultural Economics*. 77 (1995): 20-32.

[2] Albert, J., S. Chib. “Bayesian Analysis of Binary and Polychotomous Response Data”. *Journal of the American Statistical Association*. 88 (1993): 669-679.

[3] Al-Kaisi, M., H. M. Hanna. “Demonstration of Integrated Conservation Tillage and Manure Management Systems for Corn in Corn-Soybean rotations-Hub and Spokes”. Ames, Iowa State University. 2005. [Online] http://extension.iastate.edu /Publications/

[4] Al-Kaisi, M., M. A. Licht. “Effect of Strip Tillage on Corn Nitrogen Uptake and Residual Soil Nitrate Accumulation Compared with No-Tillage and Chisel Plow”. *Agronomy Journal.* 96 (2004): 1164-1171.

[5] Beyaert, R. P., J. W. Schott, P. H. White. “Tillage Effects on Corn Production in a Coarse-Textured Soil in Southern Ontario”. *Agronomy Journal.* 94 (2002): 767-774.

[6] Blackmer, A.M. “Bioavailability of Nitrogen”. In M. E. Sumner (ed.) *Handbook of soil science.* CRC Press. Boca Raton. FL. 2000. D3-D18.

[7] Bundy, L. G., T. W. Andraski, and R. P. Wolkowski. “Nitrogen Credits in Soybean-Corn Crop Sequences on Three Soils”. *Agronomy Journal.* 85 (1993): 1061-1067.

[8] Buzicky, G.C., G.W. Randall, R.D. Hauck, and A.C. Caldwell. “Fertilizer N Losses from a Tile-Drained Mollisol as Influenced by Rate and Time of 15-N Depleted Fertilizer Application”. In *Agronomy abstracts*. ASA, Madison, WI. 1983. p. 213.

[9] Christensen, L. A. “ Soil, Nutrient, and Water Management Systems Used in U.S. Corn Production”. *USDA. Agriculture Information Bulletin* (No.774). 2002.

[10] Cooper, J. C., R. W. Keim. “Incentive Payments to Encourage Farmer Adoption of Water Quality Protection Practices”. *American Journal of Agricultural Economics*. 22 (1996): 54-64.

[11] Deb, P., M. K. Munkin, P. K. Trivedi. “Bayesian Analysis of the Two-Part Model with Endogeneity: Application to Health Care Expenditure”. *Journal of Applied Econometrics.* 21:7 (2006): 1081-1099.

[12] Denbaly, M., and H. Vroomen . “Elasticities of Fertilizer Demands for Corn in the Short and the Long Run. A Cointegrated and Error Correcting System”. *American Journal of Agricultural Economics*. 75 (1993): 203-209.

[13] Dillon, C. “Production Practice Alternatives for Income nd Suitable Field Day Risk Management”. *Journal of Agricultural and Applied Economics.* 31 (1999): 247-261.

[14] Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. “Nitrogen Management Strategies to Reduce Nitrate Leaching in Tile-Drained Midwestern Soils”. *Agronomy Journal.* 94 (2002): 153-171.

[15] Dorfman, J. H. “Modeling Multiple Adoption Decisions in a Joint Framework”. *American Journal of Agricultural Economics*. 78 (1996): 547-557.

[16] Feinerman, E., E. K. Choi, S. R. Johnson. “Uncertainty and Split Nitrogen Application in Corn Production”. *American Journal of Agricultural Economics.* 72 (1990): 975-984.

[17] Fletcher, J. J., A. M. Featherstone. “An Economic Analysis of Tillage and Timeliness Interactions in Corn-Soybean Production”. *North Central Journal of Agricultural Economics*. 9 (1987): 207-215.

[18] Fuglie, K. O. “Conservation Tillage and Pesticide Use in the Cornbelt”. *Journal of Agricultural and Applied Economics*. 31 (1999): 133-47.

[19] Gentry, L. E., F.E. Below, M.B. David, J. A. Bergerou. “Source of the Soybean N Credit in Maize Production”. *Plant and Soil*. 236 (2001): 175-84.

[20] Geweke, J. “Efficient Simulation from the Multivariate Normal and Student-t Distributions Subject to Linear Constraints”. In Keramidas E. M. (ed.) *Computing Science and Statistics: Proceedings of the 23rd Symposium on the Interface*. (1991): 571-578.

[21] Gilliam, J.W., and G.D. Hoyt. “Effect of Conservation Tillage on Fate and Transport of Nitrogen”. In T.J. Logan et al. (ed.) *Effects of Conservation Tillage on Groundwater Quality: Nitrates and Pesticides*. Lewis Publ. Chelsea. (1987): 217–240.

[22] Griliches, Z. “Agricultural Output and the Demand for Input: The Demand for Inputs in Agriculture and a Derived Supply Elasticity” *Journal of Farm Economics*. 41 (1959): 309-322.

[23] Griliches, Z. “The Demand for Fertilizer: An Economic Interpretation of a Technical Change”. *Journal of Farm Economics*. 40 (1958): 591-606.

[24] Halvorson, A. D., A. R. Mosier, C. A. Reule, W. C. Bausch. “Nitrogen and Tillage Effects on Irrigated Continuous Corn Yields”. *Agronomy Journal.* 98 (2006): 63-71.

[25] Huang, W., R.G. Heifner, H. Taylor, and N. D. Uri. “Timing Nitrogen Fertilizer Application to Reduce Nitrogen Losses to the Environment”. *Water Resource Management.* 14 (2000): 35-58.

[26] Huang, W., T.I. Hewitt, and D. Shank. “An Analysis of On-Farm Costs of Timing N Applications to Reduce N Losses”. *Journal of Agricultural and Resource Economics.* 23:2 (1998): 445-467.

[27] Huang, W., N. D. Uri. “A Note on Nitrogen Fertilizer Application Timing”. *Applied Mathematical Modeling.* 19 (1995): 35-58.

[28] Khanna M. “Sequential Adoption of Site-Specific Technologies and Its Implications for Nitrogen Productivity: A Double Selectivity Model”. *American Journal of Agricultural Economics*. 83 (2001): 35-51.

[29] Khanna, M., O. F. Epouhe, R. Hornbaker. “Site-Specific Crop Management: Adoption Patterns and Incentives”. *Review of Agricultural Economics*. 21 (1999): 455-472.

[30] Koop, G., D. J. Poirier, J. L. Tobias. *Bayesian Econometric Methods*. Cambridge University Press. 2007.

[31] Korsching, P. F., C. W. Stofferahn, P. J. Nowak, and D. Wagener. “Adoption Characteristics and Adoption Patterns of Minimum Tillage: Implications for Soil Conservation Programs”. *Journal of Soil and Water Conservation*. 38 (1983): 428-30.

[32] Kurkalova, L., C. L. Kling and J. Zhao. “Green Subsidies in Agriculture: Estimating the Adoption Costs of Conservation Tillage from Observed Behavior”. *Canadian Journal of Agricultural Economics.* 54 (2006): 257-267.

[33] Li, M., D. J. Poirier, J. L. Tobias. “Do Dropouts Suffer from Dropping Out? Estimation and Prediction of Outcome Gains in Generalized Selection Models”. *Journal of Applied Econometrics*. 19 (2004): 203-225.

[34] Lichtenberg, E. "Are Green Payments Good for the Environment?". *Agricultural and Resource Economics Review*. 33 (2004): 138-147.

[35] Lichtenberg, E. “Tenants, Landlords, and Soil Conservation”. *American Journal of Agricultural Economics*. 89 (2007): 294–307.

[36] Maddala, G. S. *Limited-Dependent and Qualitative Variables in Econometrics.* Cambridge University Press. 1983.

[37] Munkin, M., P. K. Trivedi. “Bayesian Analysis of a Self-Selection Model with Multiple Outcomes Using Simulation-Based Estimation: an Application to the Demand for Healthcare”. *Journal of Econometrics*. 114 (2003): 197-220.

[38] Onianwa, O., R. Alderfer, R. A.Levins. ”Taxation as a Means of Reducing Nitrogen Fertilizer Use in Minnesota Corn Production”. University of Minnesota. Department of Applied Economics. Staff Paper P92-15. 1992.

[39] Randall, G.W., and V.A. Bandel. “Overview of Nitrogen Management for Conservation Tillage Systems: An Overview”. *In* T.J.Logan *et al*. (ed.) *Effects of Conservation Tillage on Groundwater Quality: Nitrogen and Pesticides.* Lewis Publ., Chelsea, MI. 1991. 39–63.

[40] Randall, G.W., P. R. Hill. "Fall Strip-Tillage Systems". *In* R.C. Reeder (ed.) *Conservation Tillage Systems and Management*. MWPS-45, 2nd ed. Iowa State University, Ames, IA. 2000. 193–199.

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

[42] Randall, G.W., M. A. Schmitt. "Advisability of Fall-Applying Nitrogen". In *Proceedings of 1998 Wisconsin Fertilizer, Aglime, and Pest Management Conference.* University of Wisconsin, Madison, WI. 1998. 90–96.

[43] Randall, G.W., J. A. Vetsch. "Corn Production on a Subsurface Drainage from a Corn–Soybean Rotation as Affected by Time of Nitrogen Application and Use of Nitrapyrin". *Journal of Environmental Quality*. 32 (2003): 1764–1772.

[44] Randall, G. W., J. A. Vetch. "Nitrate Losses in Subsurface Drainage from Corn-Soybean Rotation as Affected by Fall and Spring Application of Nitrogen and Nitrapyrin". *Journal of Environmental Quality*. 34 (2005): 590–597.

[45] Randall, G.W., J. A. Vetsch, and J. R. Huffman. "Nitrate Losses in Subsurface Drainage from a Corn–Soybean Rotation as Affected by Time of Nitrogen Application and Use of Nitrapyrin". *Journal of Environmental Quality*. 32 (2003): 1764–1772.

[46] Roberts, R. "Plant Nutrient Demand Functions for Tennessee with Prices of Jointly Applied Nutrients". *Southern Journal of Agricultural Economics.*18 (1986): 107-112.

[47] Roberts, R. and E. O. Heady. "Fertilizer Demand Functions for Specific Nutrients Applied to Three Major U. S. Crops". *Western Journal of Agricultural Economics*. 7 (1982): 265-277.

[48] Rotz, C. A., T. M. Harrigan. "Predicting Suitable Days for Field Operations in a Whole Farm Simulation*". An ASAE/CSAE Meeting Presentation Paper Number: 04303.* Ottawa, Ontario, Canada. August 2004.

[49] Soule, M. J. "Soil Management and the Farm Typology: Do Small Family Farms Manage Soil and Nutrient Resources Differently than Large Family Farms?" *Agricultural and Resource Economic Review*. 30 (2001): 179-188.

[50] Soule, M. J., A. Tegene, K. D. Wiebe. "Land Tenure and the Adoption of Conservation Practices". *American Journal of Agricultural Economics*. 82 (2000): 993–1005.

[51] Sharpley, A., J.J. Meisinger, A. Breeuwsma, J.T. Sims, T.C. Daniel, and J.S. Schepers. "Impacts of Animal Manure Management on Ground and Surface Water Quality". *In* J.L. Hatfield and B.A. Stewart (ed.) *Animal waste utilization: Effective use of manure as a soil resource.* Ann Arbor Press. Chelsea. MI. 1998. 173–242.

[52] Tanner, M. A., Wong, W. H. "The Calculation of Posterior Distributions by Data Augmentation (with Discussion)". *Journal of the American Statistical Association*, 82, (1987): 528-550.

[53] Torbert, H.A., and C.W. Wood. “Effects of Soil Compaction and Water-Filled Pore Space on Soil Microbial Activity and N Losses. Commun. *Soil Sci. Plant Anal.* 23(1992): 1321–1331.

[54] Uri, N. D. “The Environmental Consequences of the Conservation Tillage Adoption Decision in Agriculture in the United States”. *Water, Air, and Soil Pollution*. 103 (1998): 9-33.

[55] Uri, N. D., J. D. Atwood, and J. Sanabria. “The Environmental Benefits and Costs of the Conservation Tillage”. *Environmental Geology*. 38 (1999): 111-125.

[56] Vetsch, J.A., G.W. Randall. “Corn Production as Affected by Nitrogen Application Timing and Tillage”. *Agronomy Journal*. 96 (2004): 502-509.

[57] Vroomen, H., and B. Larson. “A Direct Approach for Estimating Nitrogen, Phosphorus, and Land Demands at the Regional Level”. USDA. ERS Technical Bulletin No. 1786. 1991.

[58] Wood, C.W., and J.H. Edwards. “Agroecosystem Management Effects on Soil Carbon and Nitrogen”. *Agric. Ecosyst. Environ*. 39 (1992): 123–138.

[59] Wu, J., 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.

[60] Wu, J., R.M. Adams, C.L. Kling, K. Tanaka. “From Microlevel Decisions to Landscape Changes: An Assessment of Agricultural Conservation Policies”. *American Journal of Agricultural Economics*. 86 (2004): 26-41.

[61] Yen, S. T. “A Multivariate Sample-Selection Model: Estimating Cigarette and Alcohol Demands with Zero Observations”. *American Journal of Agricultural Economics.* 87 (2005): 453-466.

Table 3.1. Definitions of Variables

Variables	Definition	Timing	Tillage	Yield
Fall fertilizer application	Fertilizer applied in fall (1=yes, 0=no)	X		X
Conservation tillage	Conservation tillage was used (1=yes, 0=no)		X	X
Yield	Corn yield per acre (bu)			X
College education	Farm operator had some college education (1=yes, 0=no)	X	X	X
Off-farm employment	Farmer worked off-farm (1=yes, 0=no)	X	X	
Field acreage	Number of acres in farm	X	X	
Land capability class	Land capability class is 1 or 2 (1=yes, 0=no)	X	X	X
Slope of field	Slope percentage of field (%)		X	
Manure applied	Manure was applied in field (1=yes, 0=no)	X	X	X
Rotation	Corn was rotated with a legume crop (1=yes,0=no)	X	X	X
Own land	Field owned by farm operator (1=yes, 0=no)		X	
Fieldwork days in fall	Number of days available for a fieldwork	X		
Fieldwork days in spring	Number of days available for a fieldwork		X	X
Fertilizer price in fall	Fertilizer price in fall ($/lb)	X		

Table 3.2. Descriptive Statistics of Variables

Variables	Units	Mean	St. dev.
Fall fertilizer application	Number	0.18	0.012
Nitrogen application rate in fall	Number	83.46	3.64
Conservation tillage	Number	0.78	0.12
Yield	Number	138.2	100.45
College education	Number	0.40	0.015
Off-farm employment	Number	0.60	0.046
Field acreage	Acres	68.45	14.25
Land capability class	Number	0.74	0.04
Slope of field	Number	4.21	3.63
Manure applied	Number	0.18	0.004
Rotation	Number	0.73	0.012
Land ownership	Number	0.65	0.71
Fieldwork days in fall	Days	20.64	2.125
Fieldwork days in spring	Days	16.48	1.98
Fertilizer price in fall	$ per lb	0.14	0.01
Dummy for IL	Number	0.28	0.09
Dummy for IN	Number	0.28	0.07
Dummy for OH	Number	0.27	0.08

Table 3.3a. Results: Posterior Means, Standard Deviations, and Probabilities of Being Positive.

	Fall Application			Fall Application Rate		
Variables	Mean	Std.	$\Pr(\cdot > 0 \mid y)$	Mean	Std.	$\Pr(\cdot > 0 \mid y)$
Intercept	1.41	0.33	1	5.56	2.49	1
College education	-0.017	0.02	0.21	-3.54	2.31	0.31
Off-farm employment	0.32	0.07	0.93			
Field acreage	0.43	0.06	0.92	0.52	0.098	0.85
Land capability class	0.24	0.02	0.91	0.94	0.45	0.87
Manure applied	-0.018	0.009	0.10	-43.77	1.32	0.12
Rotation	-0.17	0.03	0.06	-24.38	2.69	0.07
Fieldwork days in fall	0.43	0.23	0.92	1.48	0.57	0.95
Fertilizer price in fall	-0.53	0.19	0.12	-1.47	1.36	0.14
Dummy for IL	0.03	0.04	0.85	0.012	0.001	0.87
Dummy for IN	-0.34	0.10	0.15	-0.03	0.009	0.09
Dummy for OH	-0.32	0.10	0.08	-0.04	0.02	0.07

Table 3.3b. Results: Posterior Means, Standard Deviations, and Probabilities of Being Positive.

	Conservation Tillage			Yield		
Variables	Mean	Std.	$\Pr(\cdot > 0 \mid y)$	Mean	Std.	$\Pr(\cdot > 0 \mid y)$
Intercept	2.65	1.32	1	3.27	0.68	1
Nitrogen application rate in fall				0.75	0.22	0.91
Conservation tillage				-1.54	2.43	0.26
College education	0.32	0.13	0.93	0. 4	0.2	0.83
Off-farm employment	0.47	0.18	0.88			
Field acreage	0.26	0.05	0.91	0.50	0.07	0.81
Land capability class	0.39	0.24	0.94	3.86	2.58	0.95
Slope	0.52	0.28	0.92			
Manure applied	0.44	0.58	0.65	0.30	0.04	0.85
Rotation	0.63	0.47	0.71	2.14	0.3	0.89
Land ownership	0.51	0.38	0.93			
Fieldwork days in spring	-0.22	0.13	0.14	3.73	1.46	0.91
Dummy for IL	0.01	0.002	0.88	1.14	0.07	0.88
Dummy for IN	-0.03	0.002	0.17	-1.21	0.09	0.09
Dummy for OH	-0.01	0.015	0.24	0.56	0.11	0.84

Table 3.3c. Results: Posterior Means, Standard Deviations, and Probabilities of Being Positive.

	Yield		
Variables	Mean	Std.	$\Pr(\cdot > 0 \mid y)$
σ_{13}	0.36	0.19	0.88
σ_{23}	0.43	0.15	0.88

CHAPTER 4: CONTRACTING SPLIT FERTILIZER APPLICATION

4.1. Introduction

There is increased concern for nitrate pollution in the water from agriculture although regulating nonpoint source pollution remains one of the most difficult challenges in agricultural environmental policy. Nonetheless, the importance of nonpoint pollution problems has stimulated economic interest in the design of environmental policy for nonpoint sources. Shortle and Horan (2001) list policy mechanisms that have received significant attention in the economic literature. They discuss different economic incentives applied to inputs and practices as a part of a nonpoint water pollution control program. These include various incentive mechanisms, including charges (taxes) and subsidies, standards, pollution permits trading, contracts/bonds, and liability rules applied to inputs or practices, emission proxies, and ambient concentrations. One of incentives they list for nonpoint pollution control is a contract, under which producers agree to implement a negotiated set of practices.

There is a growing literature on using direct revelation mechanisms to design input-based contracts for nonpoint pollution control (Wu and Babcock, 1995, 1996; Smith, Tomasi, 1995; Peterson and Boisvert, 2001; Bontems and Thomas, 2006). Still, as Shortle and Horan (2001) point out, there is limited research on the design of input based instruments taking into account both moral hazard about one or more input choices and asymmetric information about land types.

This study, similar to Wu and Babcock, develops a contract to induce farmers to choose an efficient level of fertilizer application depending on the soil leaching capacity. However, in addition to asymmetric information about soil type considered by Wu and Babcock (1995,1996), the model developed here also takes into account the moral hazard problem which appears because of unobserved actions taken by some farmers. The contract requires the environmental agency to know the distribution of soil types, and pays farmers based on the total nitrogen fertilizer they apply.

For both agronomic and environmental reasons, spring post-emergent application of nitrogen fertilizer is frequently superior to fall and spring pre-emergent applications because there is less loss of nitrogen. Nitrogen fertilizer, however, is typically applied to plants in fall, early spring (spring pre-emergent fertilization) and during the growing season (spring post-emergent fertilization)[5]. Depending on weather conditions and their time constraint, farmers might choose to use split fertilizer application in order to avoid the risk of not having enough time to do it only in spring. Since actual split nitrogen applications are unobservable to the environmental regulator, the contract scheme studied here is based on total nitrogen application. There are two types of asymmetric information:

1. The amount of nitrogen applied by farmer in fall and spring, and
2. The amount of soil nitrogen runoff from fields.

The contract is signed by farmer in the fall. Significant nitrogen leaching occurs between fall and spring applications, hence soil nitrogen runoff is private information to the farmer that is observed by him/her only after the contract is signed.

The optimal contract scheme for this case can be modeled as a principal-agent problem. Regulator announces and commits himself to a contract schedule:

$$\left\{\left[Z(\alpha),T(\alpha)\right];\underline{\alpha}\le\alpha\le\bar{\alpha}\right\},$$

where α is a retention parameter (non-leaching parameter), $Z(\alpha)$ is the total nitrogen use on type α soil, and $T(\alpha)$ is the per acre payment from the environmental agency if the specified nitrogen amount is used. The regulator does not have accurate information on farmer production characteristics, particularly, the level of leaching that occurs on a farmer’s field. The soil nitrogen run-off potential is only anticipated because it depends partly on some random events such as local climatic and soil conditions. So, the contract should be designed to provide an incentive for farmers to choose the contract intended for them. Specifically, the contract should be designed such that farmers with retention parameter α_0 will voluntarily choose contract $\{Z(\alpha_0), T(\alpha_0)\}$. After accepting the contract

---

[5] The research interest is focused primarily on pre-plant fertilizer application (both fall and early spring) because of the small portion of farmers applying fertilizer in the growing season.

and before observing the true retention parameter α , the farmer decides on the amount of nitrogen he/she applies in fall. Here is moral hazard problem: the level of nitrogen application in fall should be optimal for farmer. Therefore, another challenge for the regulator in designing the contract is to induce farmers to choose the optimal level of nitrogen applied in the fall. Finally, regulators have to design a contract mechanism consistent with

- incentive compatibility or self-selection constraint – by accepting the contract, the farmer reveals his/her true type;
- individual rationality constraint – it is profitable for the farmer to accept the contract;
- moral hazard constraint – the primary nitrogen application level in fall is optimal for the farmer.

The outline of paper is following: the next section describes the previous studies related to this issue. Section 3 presents the model from farmers and regulator points of view, followed by analysis of the model for the cases of perfect and imperfect information in section 4. The next section presents the data used in the application on nitrogen pollution, and the econometric estimation used to calibrate the sequential production process. It also describes the numerical simulation conducted to compute optimal nitrogen paths. Finally, the paper concludes with a summary of findings.

4.2. Previous Literature

There is a growing literature on using direct revelation mechanisms to design input-based contracts for nonpoint pollution control. A major difficulty in agricultural contract design is that the principal (landlord, environmental agency, etc.) is frequently unable to observe some of the characteristics or actions taken by contracting agents. There are two categories of information about nonpoint sources (Tomasi, Segerson, and Braden, 1994). One is polluter's profit or control-cost type, relating to the returns to the firm from its production and pollution control choices. The second type of information is polluter's environmental type relating to information about the impact of a firm's choices on the environment. Laffont and Tirole (1993), Salanie (1998), Laffont (2002), Bolton and Dewatripont (2005) provide a modern treatment of contracting models, many of which are built upon principal-agent theory.

In the principal-agent framework, the principal has the power to design the contract, while the agent responds to the contract in a self-serving way. The principal's goal is to design the contract so as to achieve his goal, given that the agent will respond to the contract by optimizing his goals. Smith and Tomasi (1995) use mechanism design theory to develop the properties of optimal pollution control incentive schemes in the presence of adverse selection, moral hazard, and transaction costs. They demonstrate that only second-best solutions are obtainable with direct revelation mechanisms when there are transaction costs related to the collection of tax revenues.

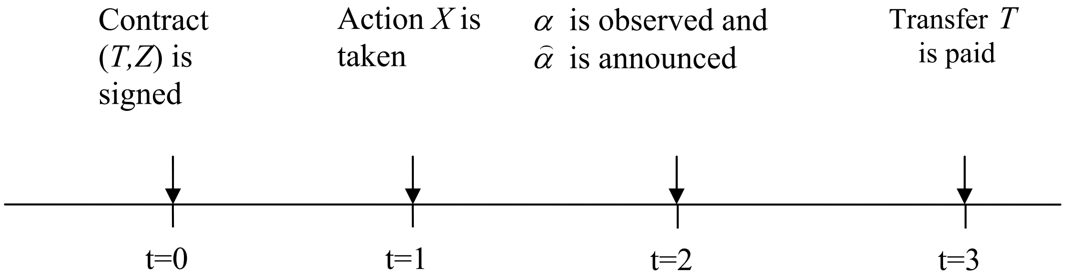
Wu and Babcock (1995) use a principal-agent model to design a green payment program under asymmetric information. Another study by Wu and Babcock (1996) develops a contract to induce land-based nonpoint polluters to choose second-best input vectors for their land type. The contract requires the environmental agency to know the distribution of land types, and pays polluters based on the land area they put under contract. Their model assumes that land types define both environmental and profit types. Analogous to Smith and Tomasi, Wu and Babcock include the social costs of tax revenue collection for funds paid to nonpoint polluters. Peterson and Boisvert (2001) empirically estimated the payments required for such a policy to reduce nitrate losses from corn production in New York. Each of the above mentioned studies focuses on the adverse selection problem, and assumes that input choices can be observed costlessly. The study of Bontem and Thomas (2006) considers a model of pollution regulation for a risk-averse farmer involving hidden information, moral hazard, and risk sharing. The farmer faces the production risk originating from nitrogen leaching. This research adds to the literature by considering the case of contract design for fall and spring fertilizer application when the regulator faces asymmetric information and moral hazard problems.

4.3. The Model

At the beginning, both agency and farmer have a common prior on parameter α, which is represented by the distribution function $G(\cdot)$ with density function $g(\cdot)$ on the interval $[\underline{\alpha}, \overline{\alpha}]$. In early spring, after the decision on fall fertilizer application, the farmer learns the true value of α before deciding on the spring one.[6] The agency gets information on α through communication with the farmer and observes only the total amount of fertilizer applied Z. Formally, the contract is the pair of functions $\{T(\beta), Z(\alpha)\}$ from $[\underline{\alpha}, \bar{\alpha}]$ to $R \times R^{+}$, depending on the farmer's report about the value of α, where T is the transfer paid by the agency to the farmer if the latter commits to apply Z amount of fertilizer in total. The total amount of fertilizer applied Z and transfer T offered to the farmer by the agency depend on the farmer's and agency's prior belief about α.

The timing then is as follows:

- at t=0, the "menu" of contracts $\{T(\alpha), Z(\alpha) : \underline{\alpha} \le \alpha \le \bar{\alpha}\}$ is offered to the farmer;
- at t=1, the farmer chooses the nitrogen fertilizer amount to apply in fall, X, to maximize his expected utility, given the prior $G(\cdot)$ on the distribution of α. Between fall and spring some fertilizer leaching and runoff occurs, therefore forcing the farmer to make second fertilizer application in spring.
- at t=2, the value of α becomes known to the farmer only and he announces value $\hat{\alpha}$ to the agency (equivalently, chooses a total nitrogen application amount $Z(\hat{\alpha})$ in the contract) or, if chooses, can get out of the contract.
- at t=3, the transfer T is paid.



---

[6] Farmers can use the late-spring nitrogen test for this purpose. The late-spring test for soil nitrate is a tool that producers use to estimate amount of available nitrogen in the soil before corn plants start intensively taking up this nitrogen.

4.3.1. Farmer's Problem

Yield generally depends on the level of available fertilizer in the soil during the growing season. Because of random weather conditions in spring, total output, in general, may be random. Output price can be random as well. However, this analysis does not consider price randomness; output price is assumed to be known too. Let A denote the residual fertilizer in the soil before fall application and X be the quantity of fertilizer applied in fall. It is suggested that carryover of fertilizer between two points in time can be approximated as a fixed portion of fertilizer available at the beginning of the period. If fertilizer retention is captured by a parameter $\alpha \in [\underline{\alpha}, \overline{\alpha}]$, then the total amount of available fertilizer in spring, B, is given by

$$B = \alpha(A + X)$$

and $\beta = 1 - \alpha$ is the proportion of available fertilizer leached between the fall and early spring.

Some of fertilizer applied in fall and early spring leaches by planting season. Hence, fertilizer uptake by the plant is assumed to be the fraction γ of fertilizer available in early spring. Let $\widetilde{Y}$ represent nitrogen take-up by the plant. Then, between dates t=1 and t=2, amount of fertilizer available for the plant is

$$\alpha(A + X)$$

and after date 2, since fertilizer applied is subject to leaching in spring, fertilizer available to the plant is

$$\widetilde{Y} = \gamma[\alpha(A + X) + Y].$$

Let F denote the underlying crop yield as an explicit function of fertilizer applications and agronomic parameters. This yields

$$F(\tilde{Y}) = F\left(\gamma\left(\alpha\left(A + X\right) + Y\right)\right)$$

Usually farmers have more time during the fall and, as a result, the opportunity cost of time is lower in the fall and higher in the spring (Randall and Schmitt, 1998; Dinnes *et al.*, 2002; Huang, Hewitt, and

Shank, 1998). Therefore, to reflect the fact that spring nitrogen application is associated with higher opportunity cost for farmer, the profit function includes the cost part that is related to nitrogen applied in spring, Y . Consequently, if farmer signs the contract his/her profit function becomes:

$$\pi = pF(\tilde{Y}) - w(X+Y) - C\left(Y\right) + T$$

where p - output price;

w - fertilizer price;

T - transfer paid by agency to the farmer;

C - cost associated with spring nitrogen application (opportunity cost of time in spring).

C is assumed to be increasing and convex function. Let Z denote total fertilizer application, $Z = X + Y$. Then yield and cost functions could be rewritten in terms of fall fertilizer application X , total application Z , and parameter α :

$$F(\tilde{Y}) \equiv f(\alpha, X, Z) \text{ and } C(Y) \equiv c(X, Z)$$

and profit now is:

$$\pi = pf(\alpha, X, Z) - wZ - C\left(Z - X\right) + T = pf(\alpha, X, Z) - wZ - c\left(X, Z\right) + T$$

Babcock and Blackmer (1994) showed that increases in a field's yield potential increase optimal fertilizer rate. Hence, the yield is assumed to be increasing and concave in amount of nitrogen available to the plant, then it follows that f is increasing in α and that $f_{\alpha Z} = \partial^2 f / \partial\alpha\partial Z$ is strictly negative:

$$\frac{\partial f}{\partial \alpha} = F' \frac{\partial \widetilde{Y}}{\partial \alpha} = F'\gamma\left(A + X\right) > 0$$

and $$\frac{\partial^2 f}{\partial \alpha \partial Z} = F''\gamma^2\left(A + X\right) - c'_Z < 0$$

The latter condition means that marginal product of fertilizer Z decreases as α increases that is, the land with lower leaching process (higher values of retention parameter α) requires lower rates of input use. This condition is called single-crossing or Spencer-Mirrlees condition and simplifies analysis of optimal contracts (Guesnerie and Laffont, 1984; Laffont and Rochet, 1998). The analysis also assumes that farmers' preferences are characterized by a strictly monotonic, increasing and strictly concave von Neumann-Morgenstern utility function denoted *U*.

The farmer's problem is to maximize the expected utility and it would be

$$\text{(FP)} \qquad \max_{X} \int \max_{Z} \left[U\left(pf(\alpha, X, Z) - wZ - c\left(X, Z\right) + T \right) \right] dG(\alpha) \qquad \text{s.t. } \; 0 \le X \le Z$$

if the farmer signs the contract, where $G(\alpha)$ is the probability distribution function for private information parameter α.

Farmer's decision making will be sequential:

1. Decides on the level of primary fertilizer application X;
2. Observes true value of leaching parameter α;
3. Decides on the level of additional fertilizer application Y.

4.3.2. The regulator's problem

The goal of the environmental agency is to maximize expected net social surplus associated with production, where the policy instrument is a contract signed between farmer and agency. This contract specifies a level of total fertilizer application Z and a transfer T from agency to the farmer. The crucial assumptions in this case are that the contract is signed before any action the farmer can take and before the value of α is observed by the farmer and that transfer is given to the farmer at the end of season.

If a type-α farmer chooses the contract intended for a type-$\hat{\alpha}$ farmer, $\left\{T\left(\hat{\alpha}\right), Z\left(\hat{\alpha}\right)\right\}$ his per acre net return, given amount of nitrogen applied in fall, *X*, would be

$$\pi(\alpha, \hat{\alpha}, X) = pf(\alpha, X, Z(\hat{\alpha})) - wZ(\hat{\alpha}) - c\left(X, Z(\hat{\alpha})\right) + T(\hat{\alpha}).$$

However, if the farmer chooses the contract intended for him, $\{T(\alpha), Z(\alpha)\}$, his per acre net return would be $\pi(\alpha, X) \equiv \pi(\alpha, \alpha, X) = pf(\alpha, X, Z(\alpha)) - wZ(\alpha) - c\left(X, Z(\alpha)\right) + T(\alpha)$.

The incentive compatibility constraint requires that farmers who observe retention parameter α prefer $\{T(\alpha), Z(\alpha)\}$ to all other options offered in the menu. Thus, a contract menu $\{T(\alpha), Z(\alpha) : \underline{\alpha} \le \alpha \le \overline{\alpha}\}$ satisfies the incentive compatibility constraint and farmer will accept the contract if and only if

(IC) $\pi(\alpha) \equiv \pi(\alpha,\alpha) \ge \pi(\alpha,\hat{\alpha}) \qquad \forall \alpha, \forall \hat{\alpha}$

where $\hat{\alpha}$ is the type the farmer reports to the agency after the uncertainty upon α is resolved for the farmer.

Since the agency can observe only the level of total nitrogen application, Z, but not the part of it applied in the fall, X, agency has to take into account the moral hazard constraint, which requires the level of X to be optimal for the farmer:

(MH) $X \in \arg\max_{X} \int_{\underline{\alpha}}^{\overline{\alpha}} U(\pi(\alpha, X)) dG(\alpha)$

To ensure voluntary participation, the contract schedule also satisfies individual rationality constraint:

$$\pi(\alpha) \ge \pi_n(\alpha), \ \forall \alpha$$

where $\pi_n(\alpha)$ is the maximum per acre net return on land type α that can be obtained without the contract. This constraint guarantees that farmers will be at least as well-off participating in the contract program as not participating. Assuming that the reservation utility for the farmer is zero and that agency is constrained to offer minimum profit regardless of realized value of α, ex-post individual rationality constraint is:

(IR) $\pi(\alpha) \ge 0, \quad \forall \alpha.$

With fall fertilizer application, the two-three months between application and nitrogen uptake create an opportunity for significant nitrogen losses. Nitrogen can be immobilized, denitrified, washed into surface water, or leached into groundwater (Huang and Uri, 1995; Huang, Hewitt, and Shank, 1998; Dinnes *et al*., 2002; Randall and Schmitt, 1998; Uri, 1998; Blackmer, 1995). As a result, relatively heavy use of nitrogen and some other fertilizers can lead to soil acidification, changes in soil properties, and off-site environmental problems. Following Wu and Babcock (1996), this analysis assumes that pollution is represented by a pollution production function $s = h\left(\left(1-\alpha\right)\left(A+X\right)\right) = h\left(\alpha, X\right)$ associated with nitrogen leaching between fall and spring, and is the per acre pollution on soil with retention parameter α. In many cases, it is reasonable to assume that $h\left(\alpha, X\right)$ is convex in X. Given X, $h\left(\alpha, X\right)$ is decreasing in α. That is, higher retention parameters (higher values of α) are associated with smaller pollution. Assume that the agency wishes to maximize social surplus from agricultural production. Given the contract schedule $\left\{T\left(\alpha\right), Z\left(\alpha\right): \underline{\alpha} \le \alpha \le \bar{\alpha}\right\}$, social value of production on soil with retention parameter α, $S\left(\alpha, X, Z\left(\alpha\right)\right)$ is

$$S\left(\alpha, X, Z\left(\alpha\right)\right) = pf(\alpha, X, Z(\alpha)) - wZ(\alpha) - c\left(X, Z\right) - h\left(\alpha, X\right)$$

and social surplus from production is $S(\alpha, X, Z(\alpha)) - \lambda T(\alpha)$, where λ denotes the opportunity cost of public funds.

The agency's problem may be written as:

$$\text{(AP)} \qquad \max_{X, Z(\cdot), T(\cdot)} \int_{\underline{\alpha}}^{\bar{\alpha}} \left[S(\alpha, X, Z(\alpha)) - \lambda T(\alpha)\right] dG(\alpha)$$

subject to (IC), (MH), (IR), $0 \le X \le Z(\alpha)$.

Given the production and pollution technologies, the socially optimal levels of nitrogen applied in fall and in total on a soil with retention parameter α, X^e and Z^e (first-best solution), can be expressed as

$$\text{(SP)} \qquad \max_{X, Z(\cdot)} \int_{\underline{\alpha}}^{\bar{\alpha}} S(\alpha, X, Z(\alpha)) dG(\alpha)$$

with first-order conditions

$$FOC_X: \quad \int_{\underline{\alpha}}^{\overline{\alpha}} \left[pf_X\left(\alpha, X, Z(\alpha)\right) - c_X\left(X, Z(\alpha)\right) \right] dG(\alpha) = \int_{\underline{\alpha}}^{\overline{\alpha}} h_X(\alpha, X) dG(\alpha)$$

$$FOC_Z: \quad pf_Z\left(\alpha, X, Z(\alpha)\right) - c_Z\left(X, Z(\alpha)\right) = w$$

which say that socially optimal X^e should equalize the marginal private net value of production with the expected marginal damage from nitrogen fertilizer applied in the fall, and marginal private net value of production due to total nitrogen use Z^e should be equal to its private cost w.[7]

In a command and control economy with complete information, the agency would set the contract menu equal to $\left\{0, Z^e\left(\alpha\right) : \underline{\alpha} \le \alpha \le \overline{\alpha}\right\}$.

4.4. Analysis of the Model

In this section, I examine the properties of an optimal contract under two cases: (1) optimal contract under perfect information and (2) optimal contract under imperfect information.

4.4.1. Optimal contract under perfect information

Under perfect information when agency is able to observe both X and parameter α, (IC) and (MH) constraints in agency problem should be ignored. Getting an expression for transfer *T* from the profit function:

$$T(\alpha) = \pi(\alpha, X) - pf(\alpha, X, Z(\alpha)) + wZ(\alpha) + c\left(X, Z(\alpha)\right)$$

agency problem could be rewritten as:

$$\max_{X, Z(\cdot), \Pi(\cdot)} \int_{\underline{\alpha}}^{\overline{\alpha}} \left[S(\alpha, X, Z(\alpha)) - \lambda \left\{ \pi(\alpha) - pf(\alpha, X, Z(\alpha)) + wZ(\alpha) + c\left(X, Z(\alpha)\right) \right\} \right] dG(\alpha)$$

s.t. (IR), $0 \le X \le Z(\alpha)$.

---

[7] Since changing the rate of nitrogen application does not necessarily require longer application time, the marginal opportunity cost of total nitrogen applied could be equal to zero: $c_Z\left(X, Z(\alpha)\right) = 0$. However, this specification does not alter the qualitative results.

Maximizing expected welfare over X and $Z(\cdot)$ gives the following first order conditions:

$$FOC_X: \quad (1+\lambda)\int_{\underline{\alpha}}^{\bar{\alpha}}\{pf_X(\alpha,X,Z(\alpha))-c_X(X,Z(\alpha))\}dG(\alpha)=\int_{\underline{\alpha}}^{\bar{\alpha}}h_X(\alpha,X)dG(\alpha)$$
$$FOC_Z: \quad pf_Z(\alpha,X,Z(\alpha))-c_Z(X,Z(\alpha))=w$$

which say that optimal X should equalize the marginal private net value of production weighted by the social cost of public funds with the expected marginal damage from nitrogen fertilizer applied in the fall, and marginal private net value of production due to total nitrogen use, Z, should be equal to sum of its private cost, w, and marginal opportunity cost.

Finally, every type of farmer has no rent at the optimum, $\pi(\alpha)=0, \quad \forall\alpha$.

4.4.2. Optimal contract under imperfect information

In the case where neither level of fall fertilizer application X nor retention parameter α can be observed by regulator he has to take into account two sets of constraints (MH) and (IC). In order to derive the characteristics of the optimal contract schedule, four lemmas will be proven. Lemma 1 examines the properties of a self-selecting contract schedule. Lemma 2 reformulates the individual rationality constraint by using results from lemma 1. Lemma 3 derives the properties of the optimal contract schedule. Finally, lemma 4 provides with optimal payment schedule given the optimal input schedule[8].

Lemma 1. A contract schedule $\{T(\alpha), Z(\alpha): \underline{\alpha}\le\alpha\le\bar{\alpha}\}$ is self-selecting if and only if

(a) $Z'(\alpha)\le 0$

(b) $T'(\alpha)=-\left[pf_Z(\alpha,X,Z(\alpha))-w-c_Z(X,Z(\alpha))\right]Z'(\alpha)$

Condition (a) of lemma 1 indicates that a self-selecting contract should not allow more input use on soil with a high retention process (high values of α). Without signing contract, farmers would

---

[8] Reader is referred to Appendix for proves of all lemmas.

choose the total fertilizer application level so that marginal private net value of production due to total nitrogen use, Z, should be equal to sum of its private cost, w, and marginal opportunity cost:

$$FOC_Z: \quad pf_Z\left(\alpha, X, Z(\alpha)\right) - c_Z\left(X, Z(\alpha)\right) = w$$

Under contract, the fertilizer use is reduced so that $pf_Z\left(\alpha, X, Z(\alpha)\right) \geq w + c_Z\left(X, Z(\alpha)\right)$. Thus, the condition (b) of lemma 1 implies that $T'\left(\alpha\right) > 0$. So, it means that in choosing contract farmers have to tradeoff decrease in fertilizer application level with increase in transfer payments from environmental agency. Taking the total derivative of the profit with respect to α it follows:

$$\pi'\left(\alpha, X\right) = pf_z \frac{\partial z}{\partial \alpha} + pf_\alpha - w\frac{\partial z}{\partial \alpha} - c_z \frac{\partial z}{\partial \alpha} + \frac{\partial T}{\partial \alpha}$$

And substituting condition (b) of lemma 1 gives:

$$\pi'\left(\alpha, X\right) = pf_\alpha > 0$$

where pf_α is a marginal value product of parameter α. Thus, the profit function is increasing in parameter α.

Lemma 2. For any self-selecting policy, the individual rationality constraint is satisfied when $\pi(\underline{\alpha}, X) \geq 0$.

Lemma 2 indicates that, given the incentive compatibility constraint, the individual rationality constraint will be satisfied as long as farmers with the highest leaching parameter are not worse off if they sign the contract. This implies that all farmers will participate as long as farmers with the lowest retention parameter participate.

Lemma 3. In case of no pooling and assuming an interior solution for X and Z, necessary conditions for an optimum are:

$$(i) \qquad \lambda\left(pf_Z - w - c_Z\right) = -\kappa U'\left(\pi\right) pf_{XZ} - \left(\upsilon / g\right) pf_{\alpha Z},$$

where

$$\upsilon(\alpha) = -\lambda\left(1 - G(\alpha)\right) + \kappa \int_{\alpha}^{\bar{\alpha}} \left\{ pf_X\left(u, X, Z(u)\right) - c_X\left(X, Z(u)\right) \right\} U''\left(\pi(u)\right) g(u)\, du$$

and

$$\kappa = -\frac{\displaystyle\int_{\underline{\alpha}}^{\bar{\alpha}} \left\{ \left(S_X + \lambda\left(pf_X - c_X\right)\right) g - \left(\int_{\alpha}^{\bar{\alpha}} \lambda g(u)\, du \right) pf_{\alpha X} \right\} d\alpha}{\displaystyle\int_{\underline{\alpha}}^{\bar{\alpha}} \left\{ \left(\int_{\alpha}^{\bar{\alpha}} \left\{ pf_X\left(u, X, Z(u)\right) - c_X\left(X, Z(u)\right) \right\} U''\left(\pi(u)\right) g\, du \right) pf_{\alpha X} + U'(\pi)\, pf_{XX}\, g \right\} d\alpha}$$

$$(ii) \qquad \int_{\underline{\alpha}}^{\bar{\alpha}} U'(\pi) \left\{ pf_X\left(u, X, Z(u)\right) - c_X\left(X, Z(u)\right) \right\} dG(\alpha) = 0,$$

$$(iii) \qquad \pi(\alpha, X) = \pi(\underline{\alpha}, X) + \int_{\underline{\alpha}}^{\alpha} pf_\alpha\left(u, X, Z(u)\right) du.$$

Condition (ii) is the first order condition associated with the moral hazard constraint. Condition (iii) shows the level of profit received by type-α farmer. Condition (i) says that compared to the perfect information case, two distortions should be added to the condition determining the screening variable Z:

$$\lambda\left(pf_Z\left(\alpha, X, Z(\alpha)\right) - w - c_Z\left(X, Z(\alpha)\right)\right) = -\kappa U'(\pi) pf_{XZ} - \frac{\upsilon}{g} pf_{\alpha Z}$$

This is because the agency has to take into account two sets of constraints due to unobservability of both fall nitrogen application X (moral hazard constraint defined by $-\kappa U'(\pi) pf_{XZ}$) and the retention parameter α (adverse selection constraint defined by $-\frac{\upsilon}{g} pf_{\alpha Z}$). The direction of both distortions compared to the perfect information level is ambiguous for this level of generality and depends on the specification of the model.

The distortion due to imperfect information on α comes from the fact that increasing the application level of a particular type will also increase the payment to all more efficient farmers. Even for the most efficient type, there can be overproduction or underproduction at the top $\left(\alpha = \overline{\alpha}\right)$, so that the usual result of no distortion at the top no longer holds. Indeed, in this case $\upsilon(\overline{\alpha}) = 0$ so that the distortion due to the incentive compatibility constraint disappears. But there still remains distortion due to the moral hazard constraint as indicated by (i). If the term $\left(-\kappa U'(\pi) pf_{XZ}\right)$ is positive, then this leads the environmental agency to distort downward the total amount of nitrogen applied in order to take account of the moral hazard constraint. However, if it is negative, then it leads the environmental agency to distort the total amount of nitrogen applied upward.

Lemma 4. Given the optimal input schedule, $Z^*(\alpha)$, the optimal payment, $T^*(\alpha)$, can be determined by

$$T^*(\alpha) = T^*(\underline{\alpha}) - \int_{\underline{\alpha}}^{\alpha} \left[pf_Z\left(\theta, X, Z(\theta)\right) - w - c_Z\left(X, Z(\theta)\right)\right] \left(Z^*\right)'(\theta) d\theta$$

where $T^*(\underline{\alpha})$ is selected to minimize the payment subject to $\pi(\underline{\alpha}) \geq 0$.

4.5. Empirical Application

Simulated optimal contract is used to show properties of the optimal contract. First, the data set used is presented. Then, the crop yield function is estimated for different production function specifications. Finally, estimation results are used to calibrate the optimal contract.

4.5.1. Data

The data used in this paper comes from ARMS data survey for year 2001 conducted by the Economic Research Service (ERS) and the National Agricultural Statistics Service (NASS) of the U.S. Department of Agriculture (USDA). It provides field-level information on the financial condition, production practices, resource use, and the economic well-being of U.S. farm households.

Farm operators included in the ARMS data are selected to ensure adequate coverage by state and region and to minimize reporting burden. Strata are based on state, the value of agricultural sales (farm size), and type of farm. NASS provides survey weights that account for these design features as well as for additional information available at the population level. Because of the complex design of the survey, all official estimates from the survey should be properly weighted. Therefore, NASS recommends the design-weighted approach as appropriate for many of the analyses for users of ARMS data (Panel to Review USDA's Agricultural Resource Management Survey, National Research Council, 2007). Ignoring the survey design can result in bias estimates, and make it impossible to perform statistically valid inferences. However, by including variables related to the design of the survey as predictor variables in a model results in a new, conditional model, for which the design is ignorable. In that case, model-based inference yields the appropriate conclusions for the sample, but not necessarily for the unweighted population. Therefore, to account for the survey design of the ARMS data, I included stratums in the set of explanatory variables. Particularly, state and farm size are included as predictive variables in the model.

Data on corn production includes data for 19 states. However, only four main corn producers were chosen for analysis: Illinois, Indiana, Iowa, and Ohio. Approximately 50% of all corn grown in the U.S. is from these four states. Data set for this analysis contains 1726 observations.

4.5.2. Model Estimation and Calibration

This paragraph describes particular function specifications used for numerical simulation procedure. The farmer’s utility function has the CRRA specification. This choice is motivated by
Moschini and Hennessy (2001):

$$U(\pi) = \frac{\pi^{1-\rho}}{1-\rho},$$

There are several functional specifications of production function used in literature (Frank, Beattie, and Embleton, 1990; Feinerman, Choi, and Johnson, 1990; Yadav, Peterson, and Easter, 1997; Huang and

Uri, 1995; Llewelyn and Featherstone, 1996). Two commonly used specifications are employed and compared for the best fit[9]. Quadratic production function takes form:

$$
\begin{aligned}
f\left(\tilde{Y}\right) &= \tilde{a}_0 + \tilde{a}_1\tilde{Y} + \tilde{a}_2\tilde{Y}^2 = \tilde{a}_0 + \tilde{a}_1\gamma\left[\alpha(A+X)+Y\right] + \tilde{a}_2\left(\gamma\left[\alpha(A+X)+Y\right]\right)^2 \\
&= a_0 + a_1X + a_2X^2 + a_3Y + a_4Y^2 + a_5XY
\end{aligned}
$$

Mitscherlich-Baule production function takes form:

$$
\begin{aligned}
f\left(\tilde{Y}\right) &= \tilde{b}_1\left(1-\exp\left(\tilde{b}_2\tilde{Y}\right)\right) = \tilde{b}_1\left(1-\exp\left(\tilde{b}_2\gamma\left[\alpha(A+X)+Y\right]\right)\right) \\
&= \alpha_1\left(1-\exp\left(\alpha_2+\alpha_3X+\alpha_4Y\right)\right)
\end{aligned}
$$

where X and Y denote the fertilizer application levels in fall and spring, respectively. A particular attention has to be paid to endogeneity of explanatory variables in production function. Due to sequential nature of the model, spring fertilizer application level Y is an implicit function of fertilizer amount applied in fall X. Therefore, use of ordinary OLS gives inconsistent parameter estimates. Moreover, a double-hurdle approach is used for modeling individual farmer's decision making on whether to apply fertilizer at certain time and how much to apply[10]. According to the logic of double-hurdle models, farmers must pass two separate hurdles before they are observed to have positive fertilizer application levels. These two hurdles are the participation decision (whether to apply fertilizer during the fall) and the consumption decision (how much to apply). Following Koop, Poirier, and Tobias (2007), the participation decision of farmer *i* is assumed to be driven by a latent variable F_i^*, with

$$F_i^* = x_{1i}\beta_1 + z_{1i}\alpha_1 + \varepsilon_{1i}$$

where x_{1i} and z_{1i} are exogenous factors (such as education, land characteristics and fertilizer prices) assumed to influence the participation decision, β_1 and α_1 are parameters to be estimated, and ε_{1i}

---

[9] One of main requirements for production function, differentiability, reduced the set of possible functional specifications.

[10] Details on choice of double –hurdle approach for modeling timing of fertilizer application are given in previous chapters.

captures unobserved attributes influencing the farmer's decision. The distinction between x_{1i} and z_{1i} is that the latter variables do not enter the subsequent fertilizer application level variables and, hence, serve as instrumental variables. While the latent variable is not observed, we do observe the binary outcome F_i, where:

$$F_i = \begin{cases} 1, & F_i^* > 0 \\ 0, & F_i^* \leq 0. \end{cases}$$

The fall fertilizer consumption decision is similarly driven by a latent variable Y_{Fi}^*, where

$$Y_{Fi}^* = x_{2i}\beta_2 + \varepsilon_{2i}.$$

However, fertilizer application levels are only observed if the farmer has passed the participation hurdle; i.e., one observes

$$Y_{Fi} = \begin{cases} Y_{Fi}^* & if\ F_i^* > 0 \\ 0 & otherwise \end{cases}$$

So, final system to estimate, for the case of quadratic production function, looks like:

$$\begin{aligned} &FA_i^* = x_{1i}\beta_1 + z_{1i}\alpha_1 + \varepsilon_{1i} \\ &Y_{Fi}^* = x_{2i}\beta_2 + \varepsilon_{2i} \\ &f_i\left(\tilde{Y}\right) = a_0 + a_1 Y_{Fi}^* + a_2\left(Y_{Fi}^*\right)^2 + a_3 Y_i + a_4 Y_i^2 + a_5 Y_{Fi}^* Y_i \end{aligned}$$

Independent variables consist of farm and operator characteristics, cropping history, and soil quality determinants. It is assumed that set of variables governing the farmer's decision making regarding fall fertilizer application is the same as the set used to explain the amount of nitrogen fertilizer applied in fall (though I allow the associated parameters to differ). As noted above, for identification purposes it is necessary to include instrumental variables (denoted by z_{1i}) into the fall participation latent variable (i.e., F_i^*). The opportunity cost of labor is significantly higher during the late spring and growing season than during the fall (Huang, Hewitt, and Shank, 1998; Randall and Schmitt, 1998; Dinnes *et al.*, 2002). Therefore, the off-farm employment of the farmer can be used as an instrumental variable specific for fall fertilizer application. The variable OFF-FARM represents the number of days worked off farm. Working off-farm leaves less time for a farmer to work in the field, particularly during pre-planting and the planting season when a lot of work needs to be done in a short period of time. Working off-farm therefore increases a farmer's risk of not being able to finish everything on time and increases the opportunity cost of time for a farmer during the planting season. As a result, a farmer who works off-farm has higher probability to apply fertilizer in the fall.

Operator characteristics include formal schooling. A discrete variable describes farmer's education and takes value of 1 if farm operator had some college education and zero otherwise. Total acreage operated by the farmer was included as an indicator of size of operation. The amount of fertilizer applied is typically determined after "credit" is given for the amount of nutrients available from the soil, the previous legume crop, and livestock manure applied. Once the needed amount of fertilizer is estimated, management decisions can be made about the fertilizer application method and timing. Therefore, dummy variables for whether the field received manure and whether corn was rotated with a legume crop are included in the model. To capture the yield differences among sites, the variable land capability class was used. Dummy variable was created that takes value zero if capability class is 1 or 2 and one otherwise. The number of days available to complete fertilizer application is another important consideration in deciding on timing of fertilizer application.

Resulting system of three equations is estimated using two-stage least squares (2SLS) procedure. In a first stage, first two equations representing two hurdles in individual farmer's decision making on whether to apply fertilizer in the fall and how much to apply, are estimated simultaneously. In the second stage, the production function is estimated, and in this stage amount of fall applied nitrogen, X, is replaced with its approximation estimated in the first stage. The definitions of variables used in estimation are given in Table 4.1. Mean values and standard deviations of all variables are given in Table 4.2. According to estimation results the Mitscherlich-Baule production function exhibited the best fit (higher R-squared). Table 4.3 presents the estimation results.

Additional restrictions are introduced so the resulting system is identified. Value of A is set to 35 kg/ha=31.23 lb/acre (Bontems, Thomas, 2006; Huang *et al*., 1998; Huang, Shank, and Hewitt, 1996). Nitrate leaching losses can vary from 0% to 60% of the applied nitrogen, but losses from common grain-production systems would range from 10% to 30% of nitrogen, therefore γ is set to 0.7 (Dinnes *et al*. 2003; Randall, Mulla, 2001). Corn price and nitrogen price are set to \$2.5/bu and \$0.17/lb, respectively. Following Wu and Babcock, I set λ to be 0.35.

Cost function and damage function also take quadratic form:

$$c(Y) = dY^2 \qquad\qquad h(X) = e\left[(1-\alpha)(A+X)\right]^2$$

Their choice was motivated by Bontems and Thomas (2006), parameters d and e are chosen to obtain the average values for the total nitrogen level close to its sample mean and are set to 0.15 and 0.25 respectively. Figure 4.7 presents the damage function for different levels of primary fertilizer application *X*.

4.5.3. Numerical Simulation Procedure

This paragraph describes the numerical procedure used to solve for the optimal solution. The numerical algorithm solves for a steady point $Z(\alpha)$. The distribution function for the farmer type is assumed uniform in $[0,1]$. The details of the algorithm are as follows:

Step 1: Generate 100 values for α in the interval $[0,1]$, and choose initial values for fall fertilizer application X_0 (mean value of fall fertilizer application), and initial value for quota Z, $Z_0 = 350(1-\alpha)$.

Step 2: For every value of α compute multipliers κ and $\upsilon(\alpha)$. Corresponding integrals are calculated using Monte-Carlo simulations.

Step 3: Solve for X using a numerical root-finding method (bisection, for example).

Step 4: Compute the next value of Z, as a solution to part (i) in Lemma 3:

$$pf_Z = (w + c_Z) - \kappa U'(\pi) pf_{XZ} / \lambda - (\upsilon / g) pf_{\alpha Z} / \lambda$$

Step 5: Update parameters and variable paths, using a smoothing technique allowing for faster convergence. The smoothing parameter, weighting the new value as opposed to the former one, is set to 0.6. The algorithm stops when convergence criteria are met, i.e., when the relative change in fall and total amount of fertilizer applied is less than 1.0E-6.

4.5.4. Results

To see how presence of contract affects levels of nitrogen applied in fall and in total, several cases are considered in simulation process.

1. Private equilibrium: solution to the risk-neutral farmer's problem with $T = 0$;
2. Social equilibrium: perfect information case;
3. Social equilibrium: imperfect information for risk-neutral farmer;
4. Social equilibrium: imperfect information for risk-averse farmer $(\rho = 4)$.

Table 4.4 presents the estimations of *X*, initial nitrogen application in the fall. Results show that under regulation initial nitrogen application in the fall is lower that in the private equilibrium. Farmers tend to overapply nitrogen in the fall, and, as a result, regulator has to decrease initial nitrogen application compared to private equilibrium. Figure 4.1 presents optimal nitrogen paths $Z(\alpha)$ for all cases. Private equilibrium solution is reported for the case of risk neutrality. Private equilibrium and perfect information nitrogen paths do decrease over the interval $[\underline{\alpha}, \overline{\alpha}]$. Regulation under perfect information allows for the higher level of total nitrogen for every farmer compared to the imperfect information equilibrium.

For the risk neutrality case under imperfect information, there is a lower level of total nitrogen over the entire range of α compared to the private equilibrium and perfect information cases. In the risk neutrality case due to the cost of hidden information and moral hazard, the regulator needs to reduce the level Z of total nitrogen so that the constraint $Z \geq X$ is binding for all values of α. Also, risk-neutral farmers are partly compensated by the level of X higher than in the private equilibrium. So, in case of risk neutrality, distortions are such that the optimal policy is uniform for all farmers.

For the risk aversity case, the optimal nitrogen level is also lower than the perfect information level. Again, because of the moral hazard, regulator needs to reduce the level Z of total nitrogen. Figure 4.3 presents optimal nitrogen levels for two different risk aversity parameters $\rho = 4$ and $\rho = 2$ to see how risk aversity affects level of nitrogen application. Results show that as risk aversity parameter increases so does the level of nitrogen application.

In all contract cases there is a lower level of total nitrogen over the entire range of α compared to the private equilibrium. This results is similar to the result obtained by Wu and Babcock and that postulates that compared to the policy that eliminates all farm programs, the payment program (contract) reduces input use and pollution.

Figure 4.2 presents transfers as a function of the total nitrogen application *Z.* It shows that all farmers are taxed when information is perfect.

In case of imperfect information two distortions are added to the condition determining the screening variable Z, compared to the perfect information case. This is because the agency has to take into account two sets of constraints due to unobservability of both fall nitrogen application X (moral hazard constraint defined by $-\kappa U'(\pi) p f_{XZ}$) and the retention parameter α (adverse selection constraint defined by $-\frac{\upsilon}{g} p f_{\alpha Z}$). Figure 4.4 presents the optimal nitrogen paths for two different cases:

(1) both constraints are present and (2) only adverse selection constraint is present and moral hazard constraint is relaxed. Results show that in case of only asymmetric information on retention parameter α, the distortion to optimal nitrogen level is negative which causes agency to increase the level of nitrogen application compared to the perfect information case. It follows that the distortion due to moral hazard is positive and magnitude of it is bigger than the one of distortion due to asymmetric information on retention parameter α. As a result, in case when both constrains are present, agency has to decrease the level of total nitrogen application compared to the perfect information case.

Some of fertilizer applied in fall and early spring leaches by planting season. The fraction of fertilizer available to the plant at planting is captured by parameter γ, the value of which is not known when the contract is signed neither to the farmer nor to agency. Figure 4.5 presents the optimal nitrogen paths for two different values of parameter γ: $\gamma = 0.7$ and $\gamma = 0.4$. Results show that the lower the fraction of nitrogen available to the plant, the higher the total amount of nitrogen application level. Finally, Figure 4.6 presents the optimal nitrogen paths for two different values of λ - the opportunity cost of public funds. Results show that the higher the opportunity cost of public funds the higher the total amount of nitrogen application level.

4.6. Conclusions

This chapter presents a contract between environmental agency and a farmer that accounts for asymmetric information and moral hazard. Farmer privately observes the soil capacity in retaining nitrogen after contract is signed. The optimal contract specifies a quota for total nitrogen use, however, regulator does not know the amount of fertilizer applied in the fall and spring separately. The characteristics of optimal solutions are derived under general assumptions of farmer utility function, nitrogen damage function, and cost of spring nitrogen application. Moreover, the farmer's sequential decision model is estimated on ARMS crop production data for year 2001. Results of this model are used to simulate the optimal contract.

Compared to the perfect information case two distortions are added to the condition determining the optimal level of total nitrogen. This is because the regulator has to take into account two sets of constraints due to the unobservability of both the fall nitrogen application X and nitrogen retention parameter α . The directions of both distortions depend on particular specification of the model. In empirical application there is underproduction at the top compared to the perfect information outcome.

Additionally, simulation results have confirmed the finding of Wu and Babcock: compared to the policy that eliminates all farm programs, the payment program (contract) reduces input use and pollution.

Appendix:

Proof of Lemma 1: By definition, a contract schedule is self-selecting only if farmers maximize their net returns by reporting their true environmental characteristics. Incentive compatibility constraint

$$\pi(\alpha) \equiv \pi(\alpha, \alpha) \geq \pi(\alpha, \hat{\alpha}) \quad \forall \alpha, \forall \hat{\alpha}$$

where $\pi(\alpha, \hat{\alpha}) = pf(\alpha, X, Z(\hat{\alpha})) - wZ(\hat{\alpha}) - \mathrm{c}\left(X, Z(\hat{\alpha})\right) + T(\hat{\alpha})$ ensures that every farmer will correctly reveal his/her type. Thus, if $\left\{T\left(\alpha\right), Z\left(\alpha\right) : \underline{\alpha} \leq \alpha \leq \overline{\alpha}\right\}$ is self-selecting, then α should be solution to the following maximization problem:

$$\max_{\hat{\alpha}} \pi\left(\alpha, \hat{\alpha}\right) = pf(\alpha, X, Z(\hat{\alpha})) - wZ(\hat{\alpha}) - \mathrm{c}\left(X, Z(\hat{\alpha})\right) + T(\hat{\alpha})$$

Consequently, α must satisfy the first-order and second-order conditions. First and second order derivatives of profit function evaluated at $\hat{\alpha} = \alpha$ are:

(1) $$\left.\frac{\partial \pi}{\partial \hat{\alpha}}\right|_{\hat{\alpha}=\alpha} = pf_z \frac{\partial z}{\partial \alpha} - w \frac{\partial z}{\partial \alpha} - c_z \frac{\partial z}{\partial \alpha} + \frac{\partial T}{\partial \alpha} = 0$$

(2) $$\left.\frac{\partial^2 \pi}{\partial \left(\hat{\alpha}\right)^2}\right|_{\hat{\alpha}=\alpha} = p\left[f_{zz}\left(\frac{\partial z}{\partial \alpha}\right)^2 + f_z \frac{\partial^2 z}{\partial \alpha^2}\right] - w\frac{\partial^2 z}{\partial \alpha^2} - c_{zz}\left(\frac{\partial z}{\partial \alpha}\right)^2 - c_z \frac{\partial^2 z}{\partial \alpha^2} + \frac{\partial^2 T}{\partial \alpha^2} \leq 0 .$$

From equation (1) follows condition (b) of lemma 1. To obtain condition (a), note that the agency selects the combination of input level and payment level for each α so that the farmer, who is selecting the optimal $\hat{\alpha}$ given that his actual retention parameter is α, will actually select his true α. Because equation (1) is true for any α, the left-hand side of this equation must be identical to zero. Therefore, its derivative with respect to α must also be identical to zero.

Taking derivative of first-order condition with respect to α yields:

$$pf_{z\alpha}\frac{\partial z}{\partial \alpha} + pf_{zz}\left(\frac{\partial z}{\partial \alpha}\right)^2 + pf_z \frac{\partial^2 z}{\partial \alpha^2} - w\frac{\partial^2 z}{\partial \alpha^2} - c_{zz}\left(\frac{\partial z}{\partial \alpha}\right)^2 - c_z \frac{\partial^2 z}{\partial \alpha^2} + \frac{\partial^2 T}{\partial \alpha^2} = 0$$

Taking into account the second-order derivative (2) gives:

(3) $$pf_{z\alpha}\frac{\partial z}{\partial \alpha} \geq 0$$

Condition (a) follows because of the single-crossing condition $\frac{\partial^2 f}{\partial \alpha \partial Z} < 0$. Thus, the optimal quote is non-increasing in α. To show that any payment scheme satisfying conditions (a) and (b) is self-selecting, let any α and $\hat{\alpha} \in [\underline{\alpha}, \overline{\alpha}]$,

(4) $$\pi(\alpha, \alpha, X) - \pi(\alpha, \hat{\alpha}, X) = \int_{\hat{\alpha}}^{\alpha} \frac{\partial \pi(\alpha, \theta, X)}{\partial \theta} d\theta$$

where

(5) $$\frac{\partial \pi(\alpha, \theta, X)}{\partial \theta} = pf_Z \frac{\partial z}{\partial \theta} - w\frac{\partial z}{\partial \theta} - c_Z \frac{\partial z}{\partial \theta} + \frac{\partial T}{\partial \theta}$$

From condition (b), $T'(\theta) = -\left[pf_Z(\theta, Z(\theta)) - w - c_Z(\theta, Z(\theta))\right]Z'(\theta)$. Substituting this expression into equation (5) gives

$$\frac{\partial \pi(\alpha, \theta, X)}{\partial \theta} = p\left[f_Z(\alpha, Z(\theta)) - f_Z(\theta, Z(\theta))\right]\frac{\partial z}{\partial \theta}$$

If $\alpha \geq \hat{\alpha}$, then $f_Z(\alpha, Z(\theta)) - f_Z(\theta, Z(\theta)) \leq 0$ because of single-crossing condition $\frac{\partial^2 f}{\partial \alpha \partial Z} < 0$ and $\theta \in [\hat{\alpha}, \alpha]$. Also, by condition (a), $Z'(\alpha) \leq 0$. Therefore, the expression in integral (4) is non-negative and $\pi(\alpha, \alpha, X) - \pi(\alpha, \hat{\alpha}, X) \geq 0$. If $\alpha \leq \hat{\alpha}$, then the expression in integral (4) is non-positive but $\pi(\alpha, \alpha, X) - \pi(\alpha, \hat{\alpha}, X) \geq 0$ still holds because the direction of integration is backwards. Thus, when conditions (a) and (b) hold, the contract schedule is self-selecting.

Proof of Lemma 2: Derivative of profit with respect to α is:

$$\frac{\partial \pi}{\partial \alpha} = pf_\alpha + pf_Z \frac{\partial z}{\partial \alpha} - w\frac{\partial z}{\partial \alpha} - c_Z \frac{\partial z}{\partial \alpha} + \frac{\partial T}{\partial \alpha}$$

and taking into account (1), reduces it to

(6) $$\frac{\partial \pi}{\partial \alpha} = pf_{\alpha}$$

Then, taking into account (3), the incentive compatibility constraint under single-crossing condition can be reduced to the following set of conditions:

$$\frac{\partial \pi}{\partial \alpha} = pf_{\alpha} \quad \text{and} \quad f_{z\alpha}\frac{\partial z}{\partial \alpha} \geq 0$$

where pf_{α} is the marginal value product of the leaching process. Thus, the payment schedule should be determined such that farmers with a higher parameter α (lower leaching process) receive a larger total return (agency payment plus production profits). Otherwise, farmers with less leaching will have an incentive to claim that their leaching is high because they can always get a larger total return than farmers with high leaching soil by choosing their contracts. Moreover, given that π' is strictly positive as indicated by (6), constraint (IR) reduces to:

(7) $$\pi\left(\underline{\alpha}, X\right) \geq 0$$

Proof of Lemma 3: Now, redefine X as a state variable with respect to α, where $\dot{X} = 0$ and $X\left(\underline{\alpha}\right) = X\left(\bar{\alpha}\right)$. The moral hazard constraint on X could be rewritten as:

(8) $$\int_{\underline{\alpha}}^{\bar{\alpha}} \left[\frac{\partial U\left(\pi\left(\alpha, X\right)\right)}{\partial X}\right] dG\left(\alpha\right) = 0$$

To verify that second order condition is satisfied consider the second derivative:

$$\int_{\underline{\alpha}}^{\bar{\alpha}} \left[\frac{\partial^2 U\left(\pi\left(\alpha, X\right)\right)}{\partial X^2}\right] dG\left(\alpha\right) = \int_{\underline{\alpha}}^{\bar{\alpha}} \left[\frac{\partial^2 U\left(pf(\alpha, X, Z(\alpha)) - wZ(\alpha) - c\left(X, Z(\alpha)\right) + T(\alpha)\right)}{\partial X^2}\right] dG\left(\alpha\right) =$$

$$\int_{\underline{\alpha}}^{\bar{\alpha}} \left[\frac{\partial\left(\frac{\partial U}{\partial \pi}\left(p\frac{\partial f}{\partial X} - \frac{\partial c}{\partial X}\right)\right)}{\partial X}\right] dG\left(\alpha\right) =$$

$$\int_{\underline{\alpha}}^{\bar{\alpha}}\left(\frac{\partial^2 U}{\partial \pi^2}\left\{\left(p\frac{\partial f}{\partial X}\right)^2-\left(\frac{\partial c}{\partial X}\right)^2\right\}+\frac{\partial U}{\partial \pi}\left\{p\frac{\partial^2 f}{\partial X^2}-\frac{\partial^2 c}{\partial X^2}\right\}\right)dG(\alpha)$$

Since utility function U is monotonic, increasing and strictly concave, $\frac{\partial^2 f}{\partial X^2}\leq 0$ and $\frac{\partial^2 c}{\partial X^2}\geq 0$, for second derivative to have negative sign it is necessary that $\left(p\frac{\partial f}{\partial X}\right)^2-\left(\frac{\partial c}{\partial X}\right)^2\geq 0$, which means that marginal private benefit from additional fertilizer applied in fall should be higher than reduction in marginal opportunity cost of spring applied fertilizer because of higher application rate in fall. Then (5) could be rewritten as follows

$$\int_{\underline{\alpha}}^{\bar{\alpha}}\left[\frac{\partial U(\pi(\alpha,X))}{\partial X}\right]dG(\alpha)=\int_{\underline{\alpha}}^{\bar{\alpha}}MdG(\alpha)=0$$

where $M=U'(\pi(\alpha))\left[pf_X(\alpha,X(\alpha),Z(\alpha))-c_X(X(\alpha),Z(\alpha))\right]$. To deal with this integral constraint, define new state variable as follows

$$\dot{K}=M(\alpha,X(\alpha),Z(\alpha),\pi(\alpha))g(\alpha) \quad \text{with } K(\underline{\alpha})=K(\bar{\alpha})=0.$$

Define $\dot{Z}=-\psi$ where ψ is a control variable and Z is redefined as a state variable. Then condition (a) from Lemma 1 becomes $\psi\geq 0$.

Denote by

$$\begin{aligned}W(\alpha,X(\alpha),Z(\alpha),\pi(\alpha))&=S(\alpha,X(\alpha),Z(\alpha))+\lambda pf(\alpha,X(\alpha),Z(\alpha))\\&\quad-\lambda\left(\pi(\alpha)+wZ(\alpha)+c(X(\alpha),Z(\alpha))\right)\end{aligned}$$

Then, the agency problem (AP) could be transformed into an optimal control problem:

$$\max_{\psi}\int_{\underline{\alpha}}^{\bar{\alpha}}W(\alpha,X(\alpha),Z(\alpha),\pi(\alpha))dG(\alpha)$$

$$\text{s.t.} \qquad \dot{X}=0 \qquad\qquad (\mu)$$

$$\dot{\pi} = pf_{\alpha}\left(\alpha, X(\alpha), Z(\alpha)\right) \qquad (\upsilon)$$

$$\dot{Z} = -\psi \qquad (\sigma)$$

$$\dot{K} = M\left(\alpha, X(\alpha), Z(\alpha), \pi(\alpha)\right)g(\alpha) \qquad (\kappa)$$

$$Z(\alpha) - X(\alpha) \geq 0 \qquad (\xi_1)$$

$$\psi(\alpha) \geq 0 \qquad (\xi_2)$$

$$X(\alpha) \geq 0 \qquad (\xi_3)$$

$$X(\underline{\alpha}) = X$$

$$\pi(\underline{\alpha}) \geq 0$$

$$K(\underline{\alpha}) = K(\bar{\alpha}) = 0\,.$$

The Lagrangean for this problem is:

$$\begin{aligned}
L = \int_{\underline{\alpha}}^{\bar{\alpha}} \Big\{ &\Big[S\left(\alpha, X(\alpha), Z(\alpha)\right) + \lambda pf\left(\alpha, X(\alpha), Z(\alpha)\right) - \\
&\lambda\left(\pi(\alpha) + wZ(\alpha)\right) - c\left(X(\alpha), Z(\alpha)\right)\Big] g(\alpha) - \mu(\alpha)X' + \\
&\upsilon(\alpha)\left(pf_{\alpha}\left(\alpha, X(\alpha), Z(\alpha)\right) - \pi'(\alpha)\right) - \sigma(\alpha)\left(\psi + Z'(\alpha)\right) + \\
&\kappa(\alpha)\left(M\left(\alpha, X(\alpha), Z(\alpha), \pi(\alpha)\right)g(\alpha) - \dot{K}\right) + \xi_1(\alpha)\left(Z(\alpha) - X(\alpha)\right) + \\
&\xi_2(\alpha)\psi(\alpha) + \xi_3(\alpha)X(\alpha)\Big\} d\alpha
\end{aligned}$$

Integrating by parts and applying the initial terminal conditions gives:

$$\int_{\underline{\alpha}}^{\bar{\alpha}} \mu(\alpha)X'(\alpha)d\alpha = -\int_{\underline{\alpha}}^{\bar{\alpha}} \mu'(\alpha)X(\alpha)d\alpha,$$

$$\int_{\underline{\alpha}}^{\bar{\alpha}} \kappa(\alpha)K'(\alpha)d\alpha = -\int_{\underline{\alpha}}^{\bar{\alpha}} \kappa'(\alpha)K(\alpha)d\alpha\,,$$

$$\int_{\underline{\alpha}}^{\bar{\alpha}} \sigma(\alpha) Z'(\alpha) d\alpha = -\int_{\underline{\alpha}}^{\bar{\alpha}} \sigma'(\alpha) Z(\alpha) d\alpha,$$

because $\sigma(\underline{\alpha}) = \sigma(\bar{\alpha}) = 0$ ($Z(\underline{\alpha})$ and $Z(\bar{\alpha})$ are free) and $\mu(\underline{\alpha}) = \mu(\bar{\alpha}) = 0$ ($X(\underline{\alpha}) = X$ and $X(\bar{\alpha})$ is free).

Thus, after plugging these expressions into the Lagrangian and omitting α for simplicity, it becomes

$$L = \int_{\underline{\alpha}}^{\bar{\alpha}} H(\alpha, X, Z, \pi, \pi', \psi, K) d\alpha$$

where

$$\begin{aligned} H(\alpha, X, Z, \pi, \pi', \psi, K) &= W(\alpha, X, Z, \pi) g + \upsilon\left(pf_\alpha(\alpha, X, Z) - \pi'\right) + \mu' X \\ &\quad - \sigma\psi + \sigma' Z + \kappa M(\alpha, X, Z, \pi) g + \kappa' K + \xi_1(Z - X) + \xi_2\psi + \xi_3 X \end{aligned}$$

Then, pointwise maximizations give the following necessary conditions:

(9) $\dfrac{\partial H}{\partial \psi} = -\sigma + \xi_2 \leq 0$ and if $-\sigma + \xi_2 < 0$ then $\psi = 0$.

Moreover, there is a complementary slackness condition:

$\xi_2 \geq 0, \quad \psi \geq 0$ and $\xi_2 \psi = 0$

So that, whenever $\psi > 0$, then $\sigma(\alpha) = \xi_2(\alpha) = 0$.

(10) $\dfrac{\partial H}{\partial X} = W_X g + \upsilon p f_{\alpha X} + \mu' + \kappa M_X g - \xi_1 + \xi_3 = 0$,

(11) $\dfrac{\partial H}{\partial K} = \kappa' = 0 \quad \Rightarrow \kappa(\alpha) = \kappa$ everywhere,

(12) $\dfrac{\partial H}{\partial Z} = W_Z g + \upsilon p f_{\alpha Z} + \sigma' + \kappa M_Z g + \xi_1 = 0$

with the following slackness conditions:

$\xi_1 \geq 0, \quad Z - X \geq 0$ and $\xi_1(Z - X) = 0$,

$\xi_3 \geq 0, \quad X \geq 0$ and $\xi_3 X = 0$,

And transversality conditions:

$$(13) \qquad \sigma(\underline{\alpha}) = \sigma(\bar{\alpha}) = 0, \qquad \mu(\underline{\alpha}) = \mu(\bar{\alpha}) = 0$$

With regard to π, consider the derivative of L with respect to π in the direction of any arbitrary differentiable function $l(\alpha)$ satisfying $l(\alpha) > 0$ and $l(\underline{\alpha}) = 0$. Let's define $\tilde{\pi}(\alpha) = \pi(\alpha) + tl(\alpha)$ with t a real number and $I(t) = L(\pi + tl)$. Assume that π is optimal which means that function I is maximum at 0, then a necessary condition is $I'(0) = 0$ which can be written as follows:

$$I'(0) \equiv \frac{\partial L}{\partial \pi} l = \lim_{t \to 0} \frac{L(\pi + tl) - L(\pi)}{t} =$$

$$-\int_{\underline{\alpha}}^{\bar{\alpha}} \left\{ \lambda lg + \upsilon l' - \kappa (pf_X - c_X) U''(\pi) lg \right\} d\alpha$$

or

$$(14) \qquad -\int_{\underline{\alpha}}^{\bar{\alpha}} \left[\lambda - \kappa (pf_X - c_X) U''(\pi) \right] lg d\alpha - \int_{\underline{\alpha}}^{\bar{\alpha}} \upsilon l' d\alpha = 0$$

Denote by

$$B(\alpha) = -\int_{\alpha}^{\bar{\alpha}} \left[\lambda - \kappa (pf_X - c_X) U''(\pi(u)) \right] g(u) du$$

Then (14) can be rewritten as

$$-\int_{\underline{\alpha}}^{\bar{\alpha}} B'(\alpha) l(\alpha) d\alpha - \int_{\underline{\alpha}}^{\bar{\alpha}} \upsilon(\alpha) l'(\alpha) d\alpha = 0$$

Integrating by parts the first integral and rearranging terms gives:

$$(15) \qquad -\left[B(\alpha) l(\alpha) \right]_{\underline{\alpha}}^{\bar{\alpha}} + \int_{\underline{\alpha}}^{\bar{\alpha}} \left(B(\alpha) - \upsilon(\alpha) \right) l'(\alpha) d\alpha = 0$$

Since l is arbitrary, it can be chosen so that $l(\underline{\alpha}) = 0$. Moreover, $B(\bar{\alpha}) = 0$.

Finally (15) implies that

$$\upsilon(\alpha) = B(\alpha),$$

or

$$\text{(16)} \quad \upsilon(\alpha) = -\int_{\alpha}^{\bar{\alpha}} \lambda g(u)\,du$$

$$+\kappa \int_{\alpha}^{\bar{\alpha}} \left\{ p f_X\left(u, X(u), Z(u)\right) - c_X\left(X(u), Z(u)\right) \right\} U''\left(\pi(u)\right) g(u)\,du.$$

Plugging (16) into (10) and assuming an interior solution for X and Z $(\xi_1 = \xi_3 = 0)$ gives:

$$\mu' = -W_X g - \left[-\int_{\alpha}^{\bar{\alpha}} \lambda g(u)\,du \right.$$

$$\left. +\kappa \int_{\alpha}^{\bar{\alpha}} \left\{ p f_X\left(u, X(u), Z(u)\right) - c_X\left(X(u), Z(u)\right) \right\} U''\left(\pi(u)\right) g(u)\,du \right] p f_{\alpha X} - \kappa M_X g.$$

Integrating and using (13), yields:

$$\int_{\underline{\alpha}}^{\bar{\alpha}} \mu' d\alpha = 0 = \int_{\underline{\alpha}}^{\bar{\alpha}} \left\{ W_X g - \left(\int_{\alpha}^{\bar{\alpha}} \lambda g du \right) p f_{\alpha X} \right\} d\alpha$$

$$+\kappa \int_{\underline{\alpha}}^{\bar{\alpha}} \left\{ \left(\int_{\alpha}^{\bar{\alpha}} \{ p f_X - c_X \} U''(\pi) g(u)\,du \right) p f_{\alpha X} + M_X g \right\} d\alpha.$$

Thus, the co-state variable κ is equal to:

$$\kappa = -\frac{\displaystyle\int_{\underline{\alpha}}^{\bar{\alpha}} \left\{ W_X g + \left(\int_{\alpha}^{\bar{\alpha}} \lambda g du \right) p f_{\alpha X} \right\} d\alpha}{\displaystyle\int_{\underline{\alpha}}^{\bar{\alpha}} \left\{ \left(\int_{\alpha}^{\bar{\alpha}} \{ p f_X - c_X \} U''(\pi) g(u)\,du \right) p f_{\alpha X} + M_X g \right\} d\alpha}$$

and the co-state variable $\upsilon(\alpha)$ is given by (16). Plugging these values in (12) and recalling that in the no pooling case $\sigma(\alpha)=0 \Rightarrow \sigma'(\alpha)=0$ gives (i) for an interior solution. The first order condition of farmer's program with respect to X gives (ii). Finally, integrating (6) gives (iii) which means that strictly positive information rent is left to any farmer with retention parameter $\alpha > \underline{\alpha}$.

Proof of Lemma 4: By using condition (b) of lemma 1 $T(\alpha)$ could be rewritten as

$$T(\alpha)=T(\underline{\alpha})+\int_{\underline{\alpha}}^{\alpha} T'(\theta)d\theta = T(\underline{\alpha})-\int_{\underline{\alpha}}^{\alpha}\left[pf_Z(\theta,X,Z(\theta))-w-c_Z(X,Z(\theta))\right]Z'(\theta)d\theta$$

Since a self-selecting contract should not allow more input use on soil with a low leaching process (high values of α) that follows from condition (a) of lemma 1, optimal payment scheme should offer higher payments to motivate farmers with low leaching soil to use less of input.

References

[1] Babcock, B. A., A. M. Blackmer. "The Ex Post Relationship Between Growing Conditions and Nitrogen Fertilizer Levels". *Review of Agricultural Economics*. 16 (1994): 441-450.

[2] Blackmer, A.M. "Losses of Fall-Applied Nitrogen". In *Proc. Annual Integrated Crop Management Conference.* Iowa State University. Ames, IA. 29-30 Nov. 1995. 55-59.

[3] Bolton, P., M. Dewatripont. *Contract Theory.* The MIT Press. 2005.

[4] Bontems, P., A. Thomas. "Regulating Nitrogen Pollution with Risk Averse Farmers under Hidden Information and Moral Hazard". *American Journal of Agricultural Economics*. 88 (2006): 57-72.

[5] Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. "Nitrogen Management Strategies to Reduce Nitrate Leaching in Tile-Drained Midwestern Soils". *Agronomy Journal.* 94 (2002): 153-171.

[6] Feinerman, E., E. K. Choi, S. R. Johnson. "Uncertainty and Split Nitrogen Application in Corn Production". *American Journal of Agricultural Economics*. 72 (1990): 975-984.

[7] Frank, M. D., B. R. Beattie, M. E. Embleton. "A Comparison of Alternative Crop Response Models". *American Journal of Agricultural Economics*, Vol. 72, No. 3. (Aug., 1990): 597-603.

[8] Guesnerie, R., J. J. Laffont. "A Complete Solution to a Class of Principal-Agent Problems With an Application to the Control of a Self-Managed Firm". *Journal of Public Economics.* 25 (1984): 329-369.

[9] Huang, W., L., R. W. Keim, Y. Lu, N. D. Uri, T. Kelley. “The Impact of Nitrogen Carryover Effect on Economic Activity and the Environment”. *Environmental Geology.* 34 (1998): 116-127.

[10] Huang, W., T.I. Hewitt, and D. Shank. “An Analysis of On-Farm Costs of Timing N Applications to Reduce N Losses”. *Journal of Agricultural and Resource Economics.* 23:2 (1998): 445-467.

[11] Huang, W., N. D. Uri. “A Note on Nitrogen Fertilizer Application Timing”. *Applied Mathematical Modeling.* 19 (1995): 35-58.

[12] Koop, G., D. J. Poirier, J. L. Tobias. *Bayesian Econometric Methods*. Cambridge University Press. 2007.

[13] Laffont, J. J. *The Theory of Incentives: the Principal-Agent Model*. The MIT Press. 2002.

[14] Laffont, J. J., J.C. Rochet. “Regulation of a Risk Averse Firm”.*Games and Economic Behavior.* 25 (1998): 149-173.

[15] Laffont, J. J., J. Tirole. A *Theory of Incentives in Procurement and Regulation.* The MIT Press. 1993.

[16] Llewelyn, R. V. and A. M. Featherstone. “ A Comparison of Crop Production Functions Using Simulated Data for Irrigated Corn in Western Kansas” *Agricultural Systems*. 54 (1996): 521-38.

[17] Moschini G., D.A. Hennessy. “Uncertainty, Risk Aversion, and Risk Management for Agricultural Producers”. In: Gardner and G. Rausser, Editors. *Handbook of agricultural economics*, Elsevier Science, Amsterdam, The Netherlands. 2001.

[18] Panel to Review USDA's Agricultural Resource Management Survey, National Research Council. *Understanding American Agriculture: Challenges for the Agricultural Resource Management Survey.* National Academy of Scinces. 2007.

[19] Peterson, J. M., R. N. Boisvert. “Control of Nonpoint Source Pollution through Voluntary Incentive-Based Policies: An Application to Nitrate Contamination in New York”. *Agricultural and Resource Economics Review.* 30 (2001): 127-138.

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

[21] Randall, G.W., M. A. Schmitt. ”Advisability of Fall-Applying Nitrogen”. In *Proceedings of 1998 Wisconsin Fertilizer, Aglime, and Pest Management Conference.* University of Wisconsin, Madison, WI. 1998. 90–96.

[22] Salanie, B. *The Economics of Contracts*. Cambridge MA: The MIT Press. 1998.

[23] Shortle, J. S., R. D. Horan. “The Economics of Nonpoint Pollution Control”. *Journal of Economic Surveys*. 15 (2001): 255-289.

[24] Smith, R. B. W., T. D. Tomasi. “Transaction costs and Agricultural Nonpoint-Source Water Pollution Control Policies”. *Journal of Agricultural and Resource Economics*. 20 (1995): 277-290.

[25] Tomasi, T., K. Segerson, and J. B. Braden. “Issues in the Design of Incentive Schemes for Nonpoint Source Pollution Control’, in T. Tomasi and C. Dorsi, eds., *Nonpoint Source Pollution Regulation: Issues and Policy Analysis*. (1994), Dortrecht: Kluwer Academic Publishers.

[26] Uri, N. D. “The Environmental Consequences of the Conservation Tillage Adoption Decision in Agriculture in the United States”. *Water, Air, and Soil Pollution*. 103 (1998): 9-33.

[27] Wu, J., B. A. Babcock. “Optimal Design of a Voluntary Green Payment Program Under Asymmetric Information”. *Journal of Agricultural and Resource Economics*. 20 (1995): 316-327.

[28] Wu, J., B. A. Babcock. “The Contract Design for the Purchase of Environmental Goods from Agriculture”. *American Journal of Agricultural Economics.* 78 (1996): 935-945.

[29] Yadav, S. N., W. Peterson, K. W. Easter. “Do Farmers Overuse Nitrogen Fertilizer to the Detriment of the Environment?” *Environmental and Resource Economics*. 9 (1997): 323-340.

Table 4.1. Definitions of Variables

Variables	Definition
Yield	Corn yield per acre (bu)
Fall fertilizer application	Fertilizer applied in fall (1=yes, 0=no)
Nitrogen application rate in fall	Amount of nitrogen applied (pounds)
Nitrogen application rate in spring	Amount of nitrogen applied (pounds)
College education	Farm operator had some college education (1=yes, 0=no)
Off-farm employment	Farmer worked off-farm (1=yes, 0=no)
Field acreage	Number of acres in farm
Land capability class	Land capability class is 1 or 2 (1=yes, 0=no)
Manure applied	Manure was applied in field (1=yes, 0=no)
Rotation	Corn was rotated with a legume crop (1=yes, 0=no)
Fieldwork days in fall	Number of days available for a fieldwork
Fertilizer price in fall	Fertilizer price in fall ($/lb)

Table 4.2. Descriptive Statistics of Variables

Variables	Units	Mean	St. dev.
Yield	Number	138.2	100.45
Fall fertilizer application	Number	0.18	0.012
Nitrogen application rate in fall	Lb/acre	83.46	3.64
Nitrogen application rate in spring	Lb/acre	132.5	2.86
College education	Number	0.40	0.015
Off-farm employment	Number	0.60	0.046
Field acreage	Acres	68.45	1.425
Land capability class	Number	0.74	0.04
Manure applied	Number	0.18	0.004
Rotation	Number	0.73	0.012
Fieldwork days in fall	Days	20.64	2.125
Fertilizer price in fall	$ per lb	0.14	0.01
Dummy for IL	Number	0.28	0.09
Dummy for IN	Number	0.28	0.07
Dummy for OH	Number	0.27	0.08

Table 4.3. Coefficient Estimates for the Mitscherlich-Baule Production Function

Variable	Parameter	Bootstrap St.Err.
α_1	182.63**	3.65
α_2	12.86**	1.24
α_3	0.013**	0.004
α_3	0.021*	0.009

adj. R^2= 0.636

Note: (**) – indicates significance at the 1% level and (*) – indicates significance at the 5% level

Table 4.4. Simulation Results

Case	X
Private equilibrium	125.71
Perfect information	22.47
Risk neutrality	34.86
Risk aversity	47.22

Figure 4.1. Optimal Path for Total Nitrogen Z

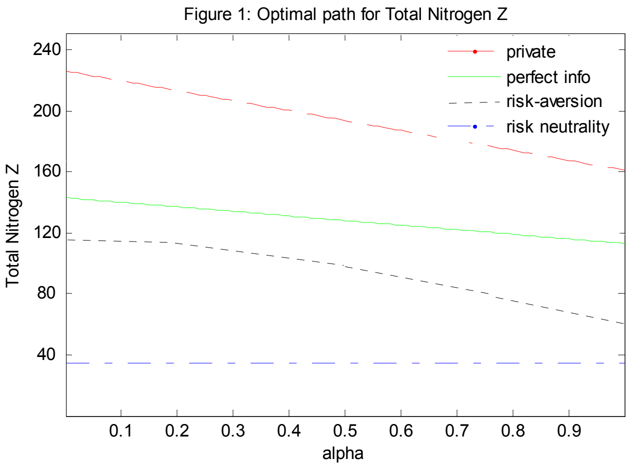


Figure 4.2. Transfer Payment

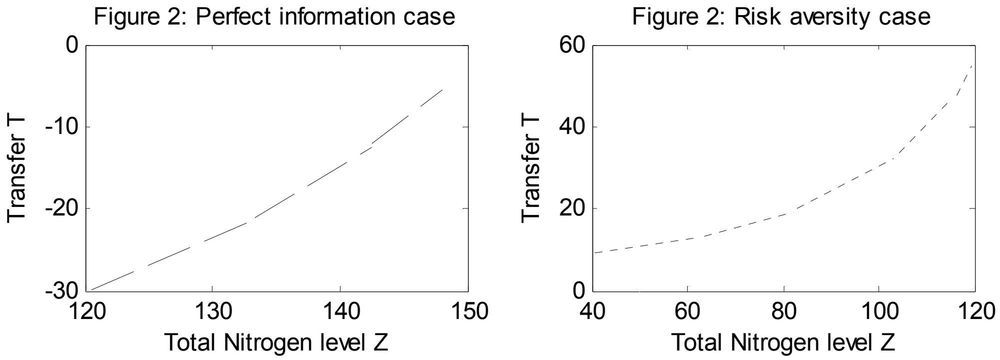


Figure 4.3. Optimal Path for Total Nitrogen Z

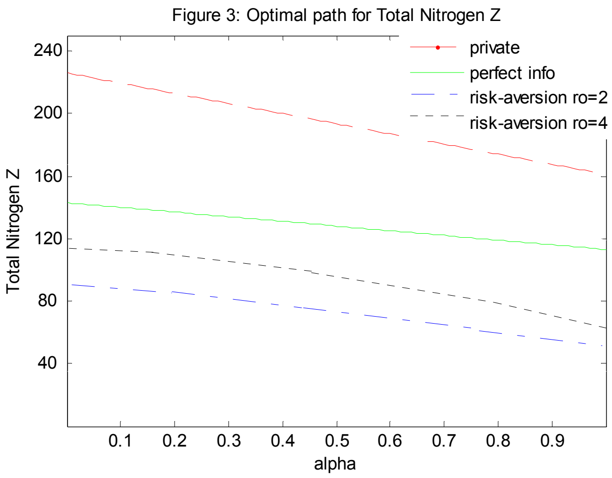


Figure 4.4. Optimal Path for Total Nitrogen Z

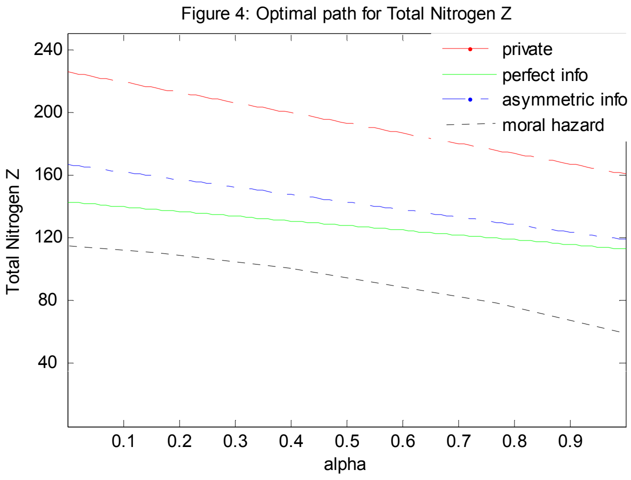


Figure 4.5. Optimal Path for Total Nitrogen Z

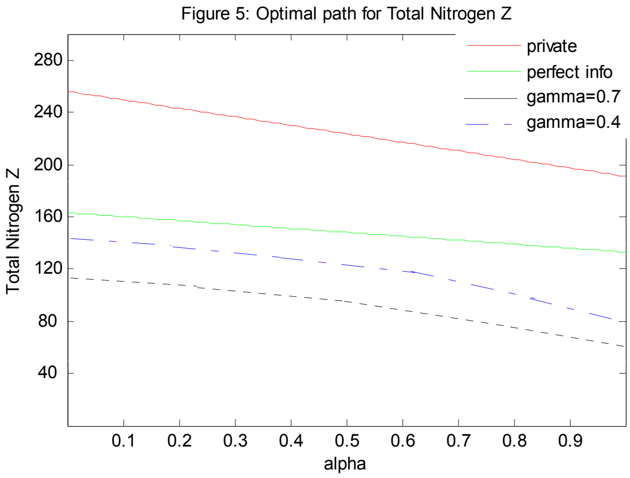


Figure 4.6. Optimal Path for Total Nitrogen Z

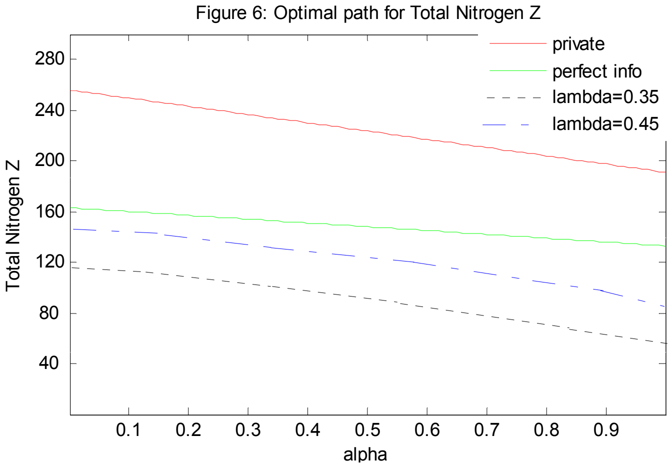
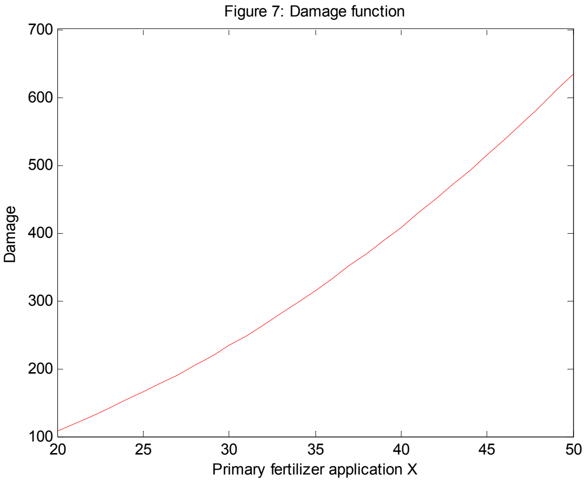


Figure 4.7. Damage function



ACKNOWLEDGEMENTS

It is a great pleasure to acknowledge the assistance and support I have received from my major professors, Dr. Catherine Kling and Dr. Joseph Herriges. Their experience, advice and vast patience in guiding me have been outstanding and inspiring. Many thanks to my committee members, Dr. Jinhua Zhao and Dr. Bruce Babcock, for their generous help, valuable advice, and insightful comments. I would also like to acknowledge the support of committee member Dr. Philip Dixon. Many thanks to Department of Economics for the scholarship I received during my program of study and giving me an opportunity to teach and conduct research, which greatly contributed to my professional growth. I also express great appreciation to my friends, who have always been inspiring and supportive. Finally, last but not least, I am particularly grateful for the love and support of my mother and my relatives.