ESSAYS ON LAND NUTRIENT POLICY, DAIRY MANAGEMENT ADJUSTMENTS AND ENVIRONMENTAL QUALITY; AND RESOURCE-BASED SUSTAINABLE DEVELOPMENT

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ESSAYS ON LAND NUTRIENT POLICY, DAIRY MANAGEMENT ADJUSTMENTS AND ENVIRONMENTAL QUALITY; AND RESOURCE-BASED SUSTAINABLE DEVELOPMENT

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In addition to a weakening demand for their products, livestock producers have faced historically high feed costs and struggle to meet increasingly stringent regulations on the management of animal wastes. In two related papers, we analyze the important linkages between farm management adjustments and changes in farm income and restrictions on land application of nutrients. Using regional and representative farm mathematical programming models, we account explicitly for new restrictions on land application of nutrients, and determine the optimal farm management responses to the regulations. Our models are specifically applied to confined animal feeding operations (CAFOs) in New York State. We incorporate into our model empirical methods for estimating environmental nutrient loading and thus determine the effects of the regulations on the distributions of nitrogen and phosphorus residuals.

The combination of our mathematical methods and the availability of two unique datasets allows for the assessment of the differential effects on income and nutrient loading for specific New York State production regions. Our results suggest that without any regulation, on-farm manure application would lead to soil nutrient levels well in excess of crop requirements. While the regulations will correct for this problem at the farm and regional levels, our results indicate that CAFOs could experience considerable income losses that depend critically on the cost of off-site

manure disposal. Our results also indicate that cropland in the region could take on enhanced value for waste disposal and that significant risks of nutrient loading remain during extreme weather events.

In a third essay, we present a stylized optimization model for Nigeria's energy sector that incorporates important social-economic objectives with traditional energy-sector planning goals of resource allocation and cost minimization. With a rapidly growing economy, Nigeria aspires to use revenue from rent of its natural resources to fund economic development. To this end, the formulation of energy-sector planning techniques has been an important objective for scholars and policy makers. We offer a new approach with our development of a resource-planning tool useful for a peculiar economic environment that integrates elements from the macroeconomics, open economy and natural resource literatures.

BIOGRAPHICAL SKETCH

Dolapo K. Enahoro was born to David and Folasade Enahoro in Ibadan, Nigeria in 1976. She attended Demonstration Secondary School in Zaria and Command Secondary School in Abakaliki, after which she attended the University of Ibadan, graduating with a Bachelor of Science in Agronomy in 2000. Her interests in agricultural management and economics led her to a Master of Science in Agricultural Economics at the University of Ibadan and to the graduate program in Applied Economics and Management at Cornell University. Upon the completion of her master's degree at Cornell in 2006, she was accepted into the PhD program in Regional Science to pursue her research interests in environmental and resource economics, planning, and farm management and production economics.

To my parents David and Folasade Enahoro; and to Edward and Efeilomo Ogon

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Members of the Winston Court Fellowship were very supportive. My grandmother, Victoria Boyejo, aunts, uncles, and cousins kept the encouragement flowing from Nigeria. Fadeke, Funlola, Boye, Toyin, uncle Gboyega, aunt Lanray and aunt Cecilia supported me and my “cause” through the years. Naalamle remained my friend through thick and thin. Edward and Efeilomo Ogon are the best siblings that anyone could hope for. I would be rooting all the way for Iquoma, Edward and Alex, just as they have done for me. My parents, David and Sade Enahoro continue to believe in me and encourage me to believe in myself. Their sacrifices and love have sustained me in many trying times. Niilante has been a rock whose calm and motivation have kept me focused. Thank you for your spirit, strength, kindness and character and for the joy that you bring.

I am thankful to God, my help and hope and the unyielding anchor for my soul.

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LIST OF ABBREVIATIONS

AFOs	Animal Feeding Operations
CAFOs	Confined Animal Feeding Operations
CES	Constant Elasticity of Substitution
CNMPs	Comprehensive Nutrient Management Plans
CO2	Carbon dioxide
CPM-Dairy	Cornell-Penn-Miner-Dairy
DDGS	Distillers Dried Grains and Solubles
DM	Dry Matter
EPIC	Erosion-Productivity Impact Calculator
GDP	Gross Domestic Product
GLEAMS	Ground Water Loading Effects of Agricultural Management Systems
MDGs	Millennium Development Goals
N	Nitrogen
NI	Nitrogen Leaching Index
NLP	Nonlinear Programming
NRCS	Natural Resources Conservation Service
P	Phosphorus
PI	Phosphorus Runoff Index
SPDES	State Pollution Discharge Elimination System
STP	Soil Test Phosphorus
TMR	Total Mixed Ration
USDA	United States Department of Agriculture
WEP	Water Extractable Phosphorus

CHAPTER 1

ASSESSMENT OF NEW YORK'S POLLUTION DISCHARGE ELIMINATION PERMITS FOR CAFOS I: REPRESENTATIVE FARM ANALYSIS[1]

Summary

Weakening demand for livestock and dairy products, historically high prices for feed ingredients and increasingly strict regulations on animal waste management continue to put significant pressure on livestock and dairy operating margins. In this paper, we use representative farm mathematical programming models to analyze important linkages between farm management adjustments and changes in farm income due to recent changes in relevant agricultural prices and restrictions on land application of nutrients. We account explicitly for new restrictions on land application of nitrogen and phosphorus that are specific to confined animal feeding operations (CAFOs).

Our mathematical methods and the distinctive data available allow for the assessment of the effects on farm income and environmental nutrient loading for New York State dairy farms. The results suggest that with current relative prices for feed ingredients, adjustments to dairy rations lead to increased nitrogen and phosphorus content in dairy waste and soil nutrient levels being applied well in excess of crop requirements. While the regulations will correct for this problem at the farm level, our results indicate that CAFOs could experience some reductions in income. Although the policy leads to reductions in nutrient loadings, our results also demonstrate that significant risks of excess nutrient loading remain during extreme weather events.

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[1] Enahoro, D., T. M. Schmit and R. N. Boisvert. New York Pollution Discharge Elimination Permits for CAFOs, Management Adjustment and the Environment: Representative Farm Analysis. In Preparation

Introduction

Reports from the USDA indicate that farm incomes declined in 2008, in part due to the global recession resulting from the collapse of international financial markets. While most agricultural producers experienced significant reductions in farm income, livestock operations and, in particular, dairy farms may have been most affected (USDA, 2009). Prior to the more recent downward pressure on milk prices from recession-driven lowered demand, dairy farmers in the Northeast also experienced a significant increase in feed prices following short-run increases in grain prices (NASS, 1991-2009). The pressure on commodity prices was mostly attributed to local expansions in the biofuels industry and increased international demand for grains and oilseeds from fast-growing economies such as China and India.

While the record-high feed costs in 2008 have moderated somewhat with the general downward movements in all commodity prices, feed costs remain well above historical levels. Thus, there continues to be significant pressure on livestock and dairy operating margins. Margins are squeezed further as dairy farmers and livestock producers struggle to meet increasingly stringent regulations on the management of animal wastes. In order to lower expenditures on animal feed, producers need to reexamine important decisions on feed composition and consider which ingredients should be grown rather than purchased. The need to lower feed costs may lead to the inclusion in the feeding regime of less conventional ingredients as distillers dried grains with solubles (DDGS). While the by-products from ethanol production offer some potential alternative feed ingredients, the switch to lower cost feed ingredients necessarily implies changes in nutrient composition in both the feeds and the manure.

Other research suggests that the recent changes in agricultural markets increase the potential for higher nutrient loadings of nitrogen and phosphorus (Schmit, *et al*., 2009). Thus, the farm management decisions on feed composition and on on-farm production must also be evaluated relative to the current regulations regarding soil nutrient applications and their effects on the environment. The research reported here analyzes the implications for New York dairy producers and environmental quality of emerging regulations on land application of nutrients. The issues that we address form part of the more general inquiry into the environmental issues associated with agricultural production.

Earlier research outlines the growing threats to water quality in the United States from increasing numbers of animal feeding operations in high agricultural production areas. The increased need to dispose of farm animal manure raises the potential for water pollution in these areas (Lander, *et al*., 1998; Kellogg, *et al*., 2000). The efficient management of soil nutrients on the animal feeding operations is thus central to achieving the goals of good water quality in the United States. This is emphasized in the Clean Water Action Plan of 1998 that seeks to minimize the negative effects of animal feeding operations on public health and the environment. Implementing the tenets of sound water quality however - while improving or maintaining the quality of surrounding waters and aiding compliance with regulation – could have significant economic implications for the farm establishment. Czymmek, *et al*. (2005), for example, suggest that it is economically challenging for confined animal feeding operations (CAFOs) to put the guidelines of new nutrient regulations into practice. In particular, the costs of transporting excess manure off-farm could prove rather prohibitive when the manure produced is of relatively high volume and low nutrient concentration. More generally, conflicts could exist for the farm operator between enhancing farm profitability by taking advantage of favorable market situations and meeting self- or regulation-imposed nutrient management objectives. This divergence underscores the need for analyses of the linkages between the farm management decisions, changes in relevant agricultural markets, and environmental policy and regulation.

The primary purpose of the research reported here is to analyze the important linkages between farm management adjustments and changes in farm income due to recent changes in relevant agricultural prices and restrictions on land application of nutrients. Because management responses to these changes in the market and increased regulation are not apparent in existing agricultural data, our analysis is based on a representative farm mathematical programming model for dairy production in New York State that accounts explicitly for new restrictions on land application of nitrogen and phosphorus, and is specific to confined animal feeding operations (CAFOs). The new restrictions are based on comprehensive nutrient management plans (CNMPs) that CAFOs must develop to obtain and/or maintain New York State's pollution discharge elimination permits that allow them to operate. In this paper, we analyze farm-level effects on environmental quality. Since the nutrient restrictions are specific to CAFOs, it is entirely possible that in direct response to the increased regulations on nutrient use, manure is exported off of CAFOs and onto farms that are not directly affected by the restrictions, increasing manure application on those lands. We investigate the effects of CAFO field nutrient regulations and farm management adjustments on regional environmental quality, in a related study.

Our research is unique in several respects. It is one of the first attempts to assess the impact of new state-specific nutrient management restrictions. In particular, we model the effects of CNMPs that set realistic crop yield objectives and the application of manure at rates consistent with soil nutrient recommendations developed by the appropriate Land Grant University, in this case Cornell University. This is made possible through the availability of two unique data sets developed for agricultural production regions in New York State: (1) the distribution of cropland on dairy farms according to crop productivity class and (2) multi-year summaries of soil nutrient tests. Using these data and results from previous research, we are also able to incorporate into our model empirical methods for estimating nutrient runoff and leaching that are calibrated specifically for New York State. We go on to estimate the effects of the regulations on the distributions of nitrogen and phosphorus residuals based on historical weather conditions. Using the distributions of nitrogen and phosphorus residuals, we are also able to interpret the results from a safety-first perspective - e.g., assessing the probabilities that these residuals will exceed certain critical thresholds with and without the regulations.

Through a set of non-linear constraints we also allow for the endogenous determination of the nutrient composition of manure from feeding various combinations of animal rations. Without any regulation, adjustments to the dairy rations that are driven by price concerns would lead to increased nitrogen and phosphorus content in dairy waste and to on-farm application of manure nutrients well in excess of crop requirements. While the regulations will correct for this problem at the farm level, CAFOs could experience reductions to income from increased manure management costs. We thus consider explicitly the cost implications of disposing of manure off-the farm. This analysis is particularly important for those dairy operations that would be required to haul manure long distances to suitable sites in compliance with the nutrient standards. We determine the manure transportation costs that inhibit the dairy farm's compliance with the new regulations.

In the next section of this paper, we outline the new nutrient restrictions guiding CAFOs in New York State. We then discuss the mathematical framework of our model and its application to the empirical setting. A description of the basic structure of the non-linear programming model follows, including the framework for investigating the dairy management adjustments to changes in DDGS prices. The data used in our study are described. Next, we show how to extend the base model to include the new nutrient application standards and to account for changes in the costs of off-site manure disposal. We then outline the empirical measurement of phosphorus runoff and nitrate runoff and leaching associated with changes in the management decisions. The results of the empirical analysis are presented and discussed. We compare solutions to the programming model and the associated implications for environmental nutrient loading, for a base case with no nutrient standards and a policy scenario in which we simulate the new nutrient regulations. Finally, we offer a summary of the work and conclusions that can be drawn.

Soil Nutrient Regulation and Management

The Clean Water Act of 1998 requires certain animal-feeding operations to develop CNMPs to minimize the detrimental effects of their operations on water quality (USDA-EPA, 1999; USDA-NRCS 2003a).[2] The setting of realistic crop yield objectives is central to the USDA criteria for implementing nutrient management plans, and thus to the CNMPs. The implementation of these plans also requires the use of reliable soil and manure nutrient tests and recommendations from the appropriate Land Grant University for the optimal rates of soil nutrient application. In the case of New York State, Cornell University is the relevant Land Grant University. The guidelines on nutrient application on New York farms take into consideration the results of soil testing for samples from agricultural lands across the state and restrict the application of soil nutrients (particularly N and P) accordingly. More generally, the states have some flexibility to adapt the federal policy to more local conditions.

[2] A 2001 proposal for revision of the Clean Water Act increased the number of animal feeding operations regulated under the Act, and further recommended that CAFOs with insufficient land be required to export excess manure to off-site recipients (For further discussion, see Feinerman, *et al*., 2004).

In New York State, CAFOs are required to obtain a pollution discharge elimination system (SPDES) permit in order to operate (NYSDEC, 2003).[3] One of the conditions for maintaining the permit is that the CAFOs develop and implement a CNMP on their farms. The CNMPs in turn are guided by the Natural Resources Conservation Service (NRCS) Code 590 standard that emphasizes the reduction of ground and surface water pollution from over-application of fertilizer and manure, and the prevention of direct manure losses to streams and lakes (USDA-NRCS, 1999).

The goal of nutrient management under the CNMPs is to ensure that the crops receive adequate nutrients during the growing season while minimizing losses of the same to surface and ground waters. Since fields could vary in their potential for environmental nutrient loading, two indicators, the Phosphorus Runoff Index (PI) and the Nitrogen Leaching Index (NLI) have been developed to aid in determining the susceptibility of fields to nutrient losses (see Ketterings, *et al*., 2003a and 2003b). We summarize the application of the PI and NLI in determining field nutrient management in the appendix (Appendix 1.A).

The NRCS nutrient guidelines rely on the use of these nutrient loss susceptibility indicators to determine N and P management on field crops in New York. On soils where the PI is the relevant index, i.e., where P loss is considered the larger threat of nutrient loading, P-based management is followed. The NLI is the important index otherwise. The nutrient standards also take into consideration the fact that the leaching indexes of the soils are highly related to soil test values. When soil P levels, for example, far exceed what P is required for optimum productivity, then there is an accumulation of P in the soil so that the nutrient may be readily available for loss to ground and surface waters. This increases the risks of P runoff from soils.

[3] Gollehon, *et al.* (2001) report that more than fifty percent of the excess manure nitrogen and two-thirds of the excess manure phosphorus generated nation-wide are produced on CAFOs.

Nitrogen-based management applies manure and commercial fertilizers at rates that supply all of the nitrogen recommendation for a crop and account for volatilization losses. Typically, this application regime results in the over application of phosphorus. P-based nutrient management on the other hand tends to make the application of nitrogen fertilizers necessary (USDA-NRCS. 1999). As outlined by the Cornell University nutrient management program, our modeling of the nutrient restrictions on N and P for field crops in New York limits crop nutrient applications to the agronomic uptake levels. We use the soil P tests as indicators of loss of P to the environment and thus restrict P application on the soils that are considered more susceptible to P loss. Further, we account for the inherent differences in nutrient management on corn, orchard grass and alfalfa acres. These conditions and allowable application rates are summarized in Figure 1.1.

P-based management is followed for fields that are considered to have *high* (i.e., soil Morgan P test of 40 lbs/acre and greater) or *medium* (i.e., test of 9 – 39 lbs/acre) risks of phosphorus run-off. While no manure or P fertilizer is allowed on high P soils, P may be applied on fields with a *medium* phosphorus index, but application is restricted to 40 percent of the P-removal rates of the crops on those fields. P application is least restrictive on the *low* STP soils, where applications can meet the entire crop P-removal requirement.

A nitrogen management regime is simultaneously applied to the crop land that accounts for the differential requirements and nitrogen utilization of the crops. For acres on which corn or orchard grass is grown, N application can not exceed the requirement levels necessary for optimum productivity for all three classifications of land based on the soil P test. Alfalfa cropping, however, allows for a little more flexibility with manure and soil nutrient management.

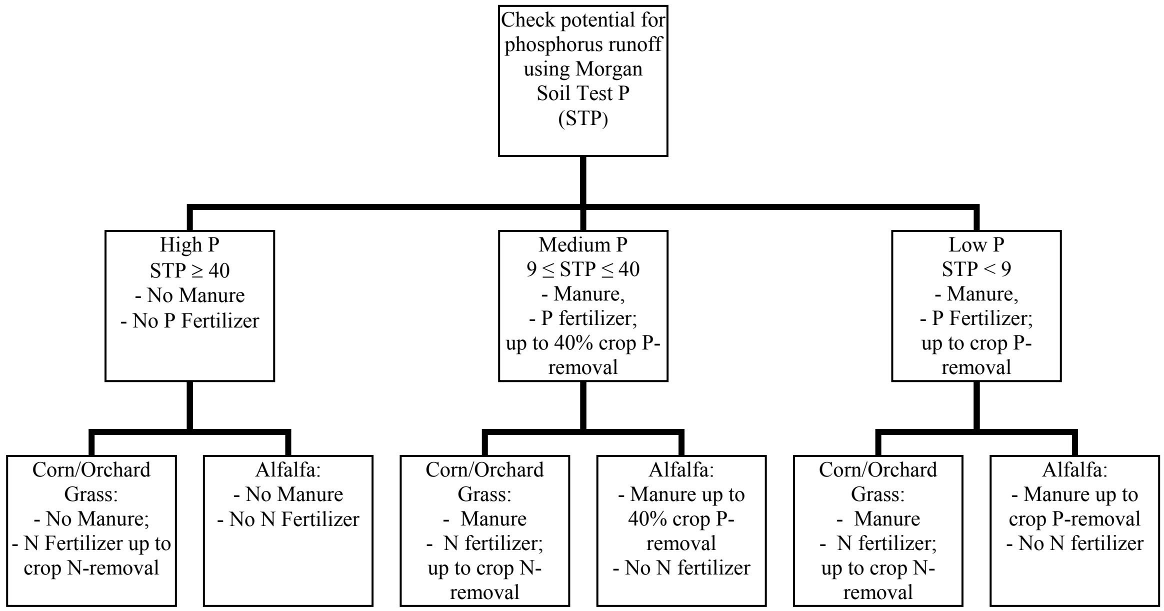

Figure 1.1. Nitrogen and phosphorus management for field crops following nutrient standards in New York

With regards to nutrient use-efficiency, alfalfa may not require any manure application since it typically meets its nitrogen requirements through N fixation. However, alfalfa has the ability to reduce its N fixation activity when other sources of N are readily available making it a better alternative for manure application (at least from an environmental loading standpoint) than corn that has had all of its N requirements met (see Ketterings, *et al.*, 2006). On the *low* and *medium* P soils, manure P application is thus allowed for alfalfa that is based on the crop's phosphorus requirements so that nitrogen is simultaneously applied. Nutrient management on the *high* P land does not allow for manure to be spread on alfalfa, recognizing the high potential for P loss.

Using relevant soil test results from New York State counties, we are able to model manure and fertilizer nitrogen and phosphorus application for CAFOs that follow the nutrient management guidelines from Cornell University. We compare the solutions to models that impose nutrient standards on N and P management to the solutions for a base case in which no nutrient standards are imposed. We thus assess the implications of the new nutrient application standards.

Mathematical Framework and Empirical Application

From as far back as the 1950's, mathematical programming methods have been applied to farm planning, including the formulation of minimum-cost animal feeds (e.g., Heady and Candler, 1958 and Waugh, 1951). While the earlier applications relied almost exclusively on linear programming methods, more recent advances have facilitated the application of both non-linear and mixed-integer models to farm planning such that the models have the enhanced capabilities to, among other functions, accommodate more realistic production relationships, relax the assumption of fixed input and output prices, accommodate management response to price and production risk and incorporate lumpy investment or management decisions (e.g., McCarl and Spreen 1980; Boisvert and McCarl 1990; Barry 1971; Cabrini, *et al*., 2004; Wui and Engle 2004).

Programming methods have also been used extensively to evaluate new opportunities and challenges facing farm operators, including the analyses of such issues as policies and management alternatives related to the interface between agricultural production and the environment (e.g. Casler and Jacobs 1975; Schmit and Knoblauch 1995; Teague, *et al.* 1995). Schmit and Knoblauch in 1995 assessed the effects of nutrient loading restrictions on the profitability of dairy farms using linear programming techniques. More recently, other studies have used mathematical programming techniques for the assessment of the implications of alternative soil nutrient application standards for manure nutrient management; to account for new nutrient management costs associated with environmental regulations compliance in the formulation of livestock feed and to analyze the economic and environmental implications of federal regulations on land nutrient application (e.g., Feinerman, *et al*., 2004; Hadrich, *et al*., 2008; Kaplan, *et al*., 2004).

Kaplan, *et al*. (2004) used a regional optimization model to provide important insights into the linkages between restrictions on the land application of nutrients, and the local economy and the environment. The constrained partial equilibrium model developed in that study was useful to illustrate the impacts of imposing nutrient standards on the largest of AFOs on various sectors of the agricultural economy – livestock, poultry and crop producers, local consumers, the environment and rural economies. In general, it was found that some of the costs of meeting the limitations on land application of nutrients on CAFOs passed through to local consumers as higher prices and to rural economies as lower production rates and labor expenditures. Further, by adopting a nation-wide approach that considered U.S. farm production regions following USDA classification, the study could account for regional differentiation in impacts of federal nutrient regulation on the sectors that were due to differences in CAFO concentration (and manure production) and land availability across the regions. The regions in the study by Kaplan, *et al*. (2004) were of relatively large geographical scope, each covering 2 to 11 states. In comparison, the studies by Feinerman, *et al*. (2004) and Hadrich, *et al*. (2008) applied mathematical programming models that accounted for nutrient standards within the context of individual U.S. states.

Feinerman, *et al*. (2004) used a mathematical programming model to determine the response of manure demand to nutrient regulations in Virginia, incorporating the identified manure demand relationships into a highly stylized spatial equilibrium model to estimate the welfare costs of alternative soil N and P application standards on manure application. Their notion of demand assumed that manure demand is by crop farmers who do not own livestock or poultry and who can choose between manure and commercial fertilizers to meet crop nutrient needs. Further, manure demand is relatively elastic and depends on the relative prices of manure and commercial fertilizers, the relative costs of spreading manure and fertilizers, manure nutrient concentration, and environmental regulations regarding the rates and methods of nutrient applications. Manure prices in turn are composed of the purchase prices at the supplier's gate and the costs of transportation to the recipient's fields.[4]

The model developed in Feinerman, *et al*. (2004) explored three alternative soil fertilization strategies – the use of commercial fertilizers only, manure only, and the applications of both fertilizers and manure. The model also took into account two major sources of manure production in Virginia - poultry litter and dairy manure; three possible scenarios for nutrient regulations - no standard, N-based management and P-based management; and a cropland availability constraint that imposed barriers to manure application in the short-term. However, the focus of the study was on the short run where manure supply was assumed to be fixed. The specification of the optimization model did not include possibilities for changes to the production activities of the animal feeding operations that could affect manure production and supply.

Hadrich, *et al*. (2008), on the other hand, allowed for variations in livestock production in their development of a model of a representative farm in Michigan. By incorporating manure management costs associated with environmental regulations in Michigan into the linear programming formulation of livestock feed rations, Hadrich, *et al*. (2008) demonstrated the possibility of formulating confined animal feed rations to minimize jointly feed and net nutrient disposal costs. This approach could account

[4] Manure suppliers could be regulated CAFOs with insufficient land to spread manure and farm gate manure prices include costs for storage and testing.

for costs of compliance with environmental regulations that may have been previously ignored.

In contrast to some cited studies, our current application of mathematical programming techniques to the assessment of soil nutrient regulations is state-specific; we follow a whole-farm management approach that allows for changes in animal and crop production and explicitly accounts for nutrient standards and nutrient management considerations in the farm manager's decisions on crop production as well as on feeding and other aspects of animal production. Further, we estimate the economic and environmental nutrient loading implications of the response of farm management to the new nutrient regulations. By comparing the estimates for nutrient leaching and runoff, we determine the effects on nutrient loading to the environment of the new guidelines for water quality as regarding CAFOs (i.e., restrictions on land application of nitrogen and phosphorus); within the contexts of changes in the market conditions (i.e., relative prices for DDGS prices) and varying economic conditions (i.e., costs of off-farm transportation of manure).

We adopt an optimization model of a representative dairy farm in New York. To account for limitations on land application of soil nutrients for CAFOs, we impose NRCS nutrient application standards following Ketterings, *et al*. (2003a; 2003b). Our specification of the nutrient regulations allows for a scenario in which there are no limits on land application of manure and commercial fertilizer nutrients and a nutrient standards scenario. It is thus possible to isolate the direct effects of the nutrient regulations. We are also able to include components in the model that link bio-energy feed ingredients, feed prices, and manure nutrient loadings by using the CPM-Dairy program.[5] Our mathematical programming model accommodates the potential for the

[5] The CPM-Dairy program, jointly developed by Cornell University, the University of Pennsylvania Veterinary College and the Miner Institute, is a software tool for formulating and evaluating dairy feed rations.

dairy operation to use lower cost feed alternatives (as in Schmit, *et al*., 2009) so that we investigate how the whole-farm nutrient management and planning responds to the use of DDGS in feed rations. The structure of the model also allows for the endogenous determination of the nutrient composition of manure from feeding the various combinations of animal rations and accounts explicitly for the cost implications of disposing manure off the farm.

Further, we use techniques developed in Boisvert, *et al*. (1997) and in Vadas, *et al*. (2009) to extend our now *non-linear* programming model to determine nitrate runoff and leaching and phosphorus loss in runoff to the environment associated with the fertilizer and dairy manure application. The nutrient loss estimation techniques that we adopt follow markedly different strategies in estimating field nutrient losses. Boisvert *et al*. (1997) derived equations for estimating N loading using N runoff and leaching data generated for specific New York soils and agro-climatic conditions using the Ground Water Loading Effects of Agricultural Management Systems (GLEAMS). On the other hand, Vadas *et al*. (2009) developed their methods for estimating P loss in runoff from extensive field studies and for a variety of soil, fertilizer management and climate conditions. The methods in Vadas *et al*. (2009) were designed to be compatible with ground water transport models such as GLEAMS and the Erosion-Productivity Impact Calculator (EPIC) model.

The Base Model and Empirical Setting

In the base model, the goal of the farm manager is assumed to be to maximize expected annual revenue over expected variable costs. The mathematical formulation of our non-linear programming (NLP) model is presented in the Appendix 1.B. The model includes the objective function and 33 sets of constraint equations. Our non-linear programming model makes use of means of input and output coefficients developed in Schmit (1994) for an optimization model of a representative dairy establishment in New York. We update the model in Schmit (1994) to address the agricultural market, nutrient management and environmental considerations relevant to the current research, and update crop and livestock budgets to reflect more recent prices paid and received. The model differentiates between the production of agricultural commodities and their uses. For example, sales activities are clearly defined for milk, cull cows and cull calves, as are activities for the purchase of crops, and the growing and the sale of farm-grown crops. Separate activities are also defined for the purchase of all feed ingredients and for major inputs such as labor, fuel, and fertilizers. The structure of the optimization model allows us to explore the potential uses of low-cost alternatives to traditional feed ingredients. It demonstrates how the composition and amounts of final feed rations are affected by relative prices of the component feed ingredients. We thus investigate including DDGS in feed rations.

The representative dairy farm in our model has characteristics similar to those of equivalently-sized farms participating in the Cornell Dairy Farm Business Summary program. Dairy cows on the representative farm are assumed to weigh 1,400 pounds and to produce 21,000 pounds of milk per cow per year on average. Milk cows, dry cows and replacement heifers are raised on rations formulated from purchased and farm-grown feed. Realistic assumptions are made about labor, livestock, and land resources available to the dairy operation. The dairy operation has 5,000 hours of labor available from the farm management or ownership, and access to additional off-farm labor at two different wage levels. Equations 1.B.8 – 1.B.10 (in Appendix 1.B) account for the three types of labor.

The maximum herd size is restricted to 250 lactating cows and the numbers of dry cows, heifers, cull cows and cull calves are constrained to be in appropriate fixed proportions to the number of milking cows (Equations 1.B.2 –1.B.5).

We use the CPM-Dairy program to generate alternative dairy rations. Ten (10) separate dairy cow activities are included in the model that differ in terms of the corn or hay-silage base and whether or not DDGS is included as a feed ingredient. Where DDGS is included, the ration may contain either 10 or 20 percent DDGS on a dry matter basis, and with a DDGS fat content of either 8 or 12 percent. The dairy cow activities are summarized in Table 1.1.

Separate activities are included for feeding dry cows and raising heifers, although these activities allow for more limited feeding options than for the lactating cows (shown in Table 1.2). For any of the feeding activities that include the bio-energy byproducts, milk production is not allowed to fall relative to the no-DDGS rations. This constraint on the results of the CPM-Dairy program has considerable empirical support.

Alfalfa hay, orchard grass, corn silage and corn for grain are either purchased or grown. The acres available limit crop production and crops grown on the farm are fed to the animals or are sold. The constraints on growing, buying and selling of crops and on their use as feed are defined in equations (1.B.12 – 1.B.15). The representative dairy operation owns or rents 620 acres of cropland on which it could produce corn (grain and silage), orchard grass and alfalfa hay following cropping rotations typical of the Central New York farming region.[6] Restrictions imposed on the crop rotations are specified in the model (Equations 1.B.31 – 1.B.33). The crop rotations influence the soil nutrient requirements of the field crops (see Table 1.3).

Land that is owned or rented by the farm is characterized by production capacity and by the soil phosphorus status; i.e., soil P test levels before applications of fertilizers and manure.

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[6] Corn silage is grown for on-farm feed but not sold.

Table 1.1: Feed rations for lactating cows based on type and level of corn distillers dried grains with solubles fed (ton DM)

	2:1 Corn Silage to Hay Crop Silage Ration[1]					1:2 Corn Silage to Hay Crop Silage Ration				
Ingredient, tons DM/yr	CS	CS0810	CS0820	CS1210	CS1220	A	A0810	A0820	A1210	A1220
Corn silage	3.07	2.95	2.90	2.90	2.90	1.40	1.40	1.42	1.40	1.40
Mixed hay silage[2]	1.51	1.45	1.43	1.43	1.43	2.84	2.84	2.81	2.84	2.84
Corn grain	0.96	0.62	0.04	0.67	0.03	1.68	1.24	0.65	1.17	0.96
Soy hulls	0.00	0.61	0.61	0.57	0.61	0.00	0.21	0.50	0.27	0.00
Wheat middlings	0.37	0.13	0.00	0.16	0.00	0.39	0.06	0.00	0.07	0.00
8% fat DDGS[3]	0.00	0.73	1.46	0.00	0.00	0.00	0.73	1.46	0.00	0.00
12% fat DDGS	0.00	0.00	0.00	0.70	1.40	0.00	0.00	0.00	0.70	1.40
Soybean meal[4]	0.70	0.45	0.30	0.40	0.31	0.56	0.30	0.08	0.30	0.30
Other[5]	0.15	0.24	0.51	0.24	0.46	0.15	0.29	0.43	0.29	0.27
Total (tons DM)	6.78	7.18	7.25	7.08	7.15	7.03	7.07	7.35	7.03	7.18
TMR CP, %	16.1	16.8	19.3	16.6	18.4	16.8	18.6	19.1	18.7	19.7
Total manure, tons/yr	21.11	21.35	21.81	21.23	21.20	22.40	22.40	21.81	22.40	22.81
N in manure, lbs/yr	247.78	269.02	332.08	261.83	307.20	265.06	304.99	325.35	305.66	337.59
P in manure, lbs/yr	29.91	30.18	36.50	29.98	34.62	30.59	30.59	34.69	30.59	40.00
Milk production[6], cwt/yr	213.50	213.50	213.50	213.50	213.50	213.50	213.50	213.50	213.50	213.50

[1] Rations are on an annual basis and are based on the CPM-Dairy program assuming a 1,400 lb Holstein cow and a 305 d lactation. Ration headings are formatted by primary forage base, DDGS fat percentage, and percentage of DDGS fed on a dry matter basis, respectively; e.g., CS0810 = primary corn silage forage base, 8% fat DDGS, and 10% DDGS fed.

[2] Mixed hay silage includes both alfalfa and grass hay crops.

[3] DDGS = corn distillers dried grains with solubles.

[4] Soybean meal includes heat-treated soybean meal, SoyPlus (West Central Coop, Ralston, Iowa).

[5] Other ingredients include blood meal, fat, Mepron (Evonik Deguss GmBH, Hanau-Wolfgang, Germany), and mineral mix.

Table 1.2: Feed rations for dry cows and replacement heifers based on type and level of corn distillers dried grains with soluble fed (tons DM/yr)

Ingredient (% CP, % fat)	Dry cow[1] DC	DC8	DC12	Replacement heifer RH	RH8	RH12
Corn silage(8.0, 3.2)	0.36	0.36	0.36	1.10	1.10	1.10
Grass silage (10.0, 3.0)	0.18	0.18	0.18	0.00	0.00	0.00
Hay silage(19.9, 3.0) [2]	0.00	0.00	0.00	1.10	1.10	1.10
Wheat straw (4.8, 2)	0.09	0.09	0.09	0.00	0.00	0.00
Corn grain (9.0, 4.2)	0.06	0.06	0.06	0.55	0.55	0.55
Soybean meal (55.0, 2.8)	0.09	0.00	0.00	0.18	0.00	0.00
Soy hulls (12.1, 2.6)	0.06	0.06	0.06	0.18	0.18	0.18
DDGS-8 (30.4, 8.0)[3]	0.00	0.12	0.00	0.00	0.32	0.00
DDGS-12 (30.4, 12.0)	0.00	0.00	0.12	0.00	0.00	0.32
Mineral-vitamin mix	0.02	0.02	0.02	0.08	0.08	0.08
Total (tons DM)	0.86	0.89	0.89	3.19	3.33	3.33
Total manure, tons/yr	2.40	2.40	2.40	7.30	7.30	7.30
N in manure, lbs/yr	33.56	29.40	29.40	165.96	164.91	164.91
P in manure, lbs/yr	4.48	5.51	5.51	14.00	17.54	17.54

[1] Rations are on an annual basis and are based on the CPM-Dairy program assuming a 1,400 lb cow for a 60 d dry period and an average 750 lb replacement heifer for 365 d. Ration headings are formatted by type of DDGS fed. DDGS were included in dry cows' rations at approx. 13% of total dry matter, heifers rations included DDGS at 10% of total dry matter, e.g., DC12 = dry cow ration with 12% fat DDGS, and RH8 = replacement heifer ration with 8% fat DDGS.
[2] Mixed hay silage includes both alfalfa and grass hay crops.
[3] DDGS = corn distillers dried grains with solubles.

Table 1.3: Nitrogen requirements for corn grain and corn silage rotations (lbs/ac)

Year in rotation	Corn grain following Alfalfa	Corn grain following Orchardgrass	Corn silage following Alfalfa	Corn silage following Orchardgrass
1	20	20	20	20
2	20	39	20	35
3	56	66	52	62
4	92	92	87	87

While land productivity class depends on the capability of the land for corn grain production, the soil phosphorus classifications indicate the levels of naturally-occurring P in the soil and build-up of residual P from previous years' applications. Table 1.4 presents the crop productivity and soil phosphorus level classifications of the land available to the representative dairy operation. It also includes summaries of the classifications for the sample of soil survey data that we apply to the representative farm model.

Table 1.4: Distribution of land on the representative dairy farm

	Mean[1] (Range)	% of Land in Class
Land (acres)	620	100
Productivity (tons of corn silage/ac)[2]		
Land Class 1	113	23
Land Class 2	121	66
Land Class 3	135	11
Soil Test P (lbs/ac)[2]		
Low	4 (0 – 8)	44
Medium	24 (9 – 39)	48
High	120 (40 – 200)	8
Hydrologic Groups		
Hydrologic Group A	-	7
Hydrologic Group B	-	31
Hydrologic Group C	-	62

[1] The means are for Western New York farm production regions as defined as in Dairy Farm Business Summaries (DFBS).

[2] The proportions of soils in the crop productivity classifications are from soil survey data as reported in Boisvert *et al*., 1997. Soil P test distributions follows Rao *et al*., 2007.

About 10 percent of the land is assumed to be of considerably high quality, where land quality classification is based on the (corn) production capability of the land. Soils in land class 1 (the lowest quality) make up about 23 percent of the soils available to the representative farm while land class 2 (medium quality) account for 66 percent of the cropland. More than half of the soils are in the medium or high soil test phosphorus category.[7]

Field Management of Nitrogen and Phosphorus and the Nutrient Standards

The soil nutrient management involves decisions on the purchase and land application of commercial fertilizers and on the use and off-site disposal of manure. Except for starter nitrogen requirements that are fulfilled using commercial fertilizers only, all crop N and P requirements on the farm can be met using either commercial fertilizers purchased from off-farm sources or manure produced on-farm. The use of animal waste as crop nutrients leads to cost-savings on commercially available nutrients; and the amount that the farm thus saves is assumed equivalent to the market value of the corresponding nutrient.

Since the amounts of nutrients available in the manure produced depend on the composition of rations fed to the animals, the demand for nutrients by the crops (and restrictions on soil nutrient applications) necessarily influence the choice of rations fed. It should be noted that the CPM-Dairy program generates output with higher amounts of N and P in manure for rations that include DDGS as feedstock (see Table 1.1). As such, relatively high prices for commercial fertilizers and increasing demand for manure nutrients could trigger the use of low-cost feed alternatives in our model.

A distinguishing feature of our current model is that we endogenize the rates of manure application, matching the amounts of manure nutrients available for crop use

[7] The proportions of soils in the crop productivity classifications are based on soil survey data as explained in Boisvert *et al*., 1997. Soil P test distributions follows Rao *et al*., 2007. The soil P test distributions are assumed constant across the soil productivity classes.

with the nutrient requirements of the crops.[8] To do this, we accumulate the total volume of manure produced from lactating and dry cows and heifers on the representative dairy farm as in Equation 1.B. 20. The amounts of N and P nutrients produced in the farm manure are similarly accumulated (Equations 1.B.21 – 1.B.22). Manure that is produced on the farm is either spread as N and P fertilizer on corn and orchard grass acres, applied on land growing alfalfa hay to meet phosphorus requirements, or transported to off-farm locations. The total manure applied (i.e., for all of the cropping activities that come into the nonlinear programming solutions) is accumulated in Equation 1.B.23. Equation 1.B.24 takes inventory of manure production, application and disposal on the farm. However, not all of the manure nutrients produced on the farm can be available for plant uptake and we account for handling, storage and field losses. Equations 1.B.25 and 1.B.26 determine N and P available for plant uptake per ton of manure that is produced. The fields' starter N requirements are fulfilled with fertilizer purchases, as shown in Equation 1.B.27. Further, the other nutrient requirements of the crops are matched to the nitrogen and phosphorus nutrients available in the manure produced.

As illustrated in the appendix, Equations 1.B.28 and 1.B.29 hold for as many cropping activities as come into solutions. We thus are able to account for field differences in the soil-crop nutrient needs. The two equations also hold simultaneously as less-than/equal-to constraints, so that manure nutrient application could just meet, or exceed the nutrient requirements, depending on the assumptions on land nutrient restrictions. Equations 1.B.28 and 1.B.29 are less-than constraints when over application of N or P is possible, and equality constraints otherwise. To concurrently fulfill N and P requirements on the fields, one of the nitrogen or phosphorus equations

[8] In Schmit (1994) and Schmit et al. (2009), average nutrient levels were assumed and manure was applied to the fields at predetermined rates of 10 or 20 tons per acre.

holds. Where the constraint on manure application is binding (as in the nutrient standards scenario) the lower of the manure application rates that meets the cropping N or P requirements is applied. Crop nutrient requirements in excess of what is available in manure can then be met in the model using commercially-available fertilizers.

We model land application of manure and commercial fertilizers under two conditions. The first case assumes no restrictions on the land application of nutrients so that the dairy operation can spread on-farm up to 100 percent of the manure that is produced[9]. Under the alternative policy simulation, farm nutrient planning follows NRCS guidelines for nutrient application to field crops. We limit P and N applications to the levels necessary for optimal crop yield and further take into consideration the potential for P losses from the fields. By assuming similarity in other important characteristics such as the field topography, we assume that the differences in potential for P loss to surrounding waters are due entirely to differences in soil P status and field nutrient management. Based on Figure 1.1, we restrict manure and fertilizer applications of phosphorus based on the soil P levels of the cropped land (i.e., for the nutrient standards scenario). To do this, we designate the cropping acres available to the representative dairy farm as being of high, medium, or low soil P status, adopting relevant means and distributions from soil survey data of soil phosphorus for farmland in high milk-producing counties in Western New York (Rao, et al., 2007). The relevant soil P test summaries that we apply to our model are reported in Table 1.4. Eight percent of the land is of high soil test phosphorus (STP); 48 percent is medium soil P; and the rest of the land is in the low soil P classification. We apply these

[9] We assume no limits to commercial and manure fertilizer application but since commercial nutrients must be purchased at market prices while manure is produced and applied at no significant additional costs to the operation, the farm in the model chooses manure over fertilizers whenever possible, and dumps on the land all manure produced in excess of requirements.

proportions to the 620 acres available to the representative dairy establishment and assume that the proportions are constant for the land productivity classes (also reported in Table 1.4).

Phosphorus application is not allowed on soils with high P and manure may not be spread on these fields. Commercial N fertilizers may however be used to fulfill N requirements, up to the agronomic N-uptake level for the crop. On soils with medium or low P, manure may be applied at the application rates at which either of P or N requirements of the crop is fulfilled, whichever is more limiting. Nutrient requirements beyond that supplied by manure at this limiting rate can then be fulfilled using either N or P single nutrient amendments. We account for available soil P in determining the agronomic P-uptake level of growing crops, thus restricting P application on medium and high soil P lands. To distinguish the no-policy (base) from the nutrient restriction scenarios in our specifications of the model, we assume in the base case that manure and fertilizers can be applied on all of the land at economically optimal rates that do not take nutrient over-application or environmental loading concerns into consideration. In the scenario that does account for over-application through the implementation of new land nutrient restrictions, there is an increased need for manure management. Transporting excess manure off the farm is one option that the representative dairy farm must consider.

Off-Site Manure Disposal

Manure that is produced on the farm and not applied to the fields as crop nutrients is assumed to be transported to off-farm recipients. This manure may be available for field application on other farms. Although there may be some merit to accounting for the cash value of the nutrients available in animal manure, it is assumed that no payment is received from the manure-importing farm. Costs associated with the off-farm land application are also not included in the model. Instead, the exporting farm incurs the cost of transporting the manure to the receiving centers. These simplifying assumptions do not distract from the focus of our farm-level analysis and are consistent with work done to assess the costs associated with the implementation by livestock operations of comprehensive nutrient management plans (USDA, NRCS 2003a). The costs of manure transportation may be a function of the volume of manure transported and the distance covered, amongst others (see Harrigan, 2001). The farm operator in our model faces an aggregate cost that encompasses manure volumes and distances. We investigate the effects of changes in off-site manure disposal costs on management adjustments by parametrically increasing the costs of transporting manure to off-farm receiving centers, from an initial low cost.

Environmental Nutrient Loading

The dairy management adjustments to dairy feed prices and new nutrient standards have implications for nutrient loading to the environment. Given the growing focus on P loading risks from agricultural operations and the development of newer water quality assessment tools useful to analyze these risks, the emphasis of our environmental analysis for the representative animal feeding operation is necessarily on P loss in runoff. We however are also able to include in our assessment something on the potential N loading associated with the farm management adjustments. This is made possible by the availability of derived equations and data for estimating N runoff and leaching specific for soils in the agricultural production region that our model is based on (Boisvert, *et. al.*, 1997). We thus examine P and N loading effects in our representative farm model using two distinct techniques for determining the distributions of phosphorus and nitrogen residuals from crop land.

To quantify the amounts of P lost to the environment due to farm nutrient management practices, we follow the methods developed in Vadas *et al*. (2009) for reliably quantifying field-level loss of P in runoff from surface-applied manure and fertilizer for a variety of soil types, crop and fertilizer management patterns, and geo-climatic conditions. According to Vadas *et al*. (2009), these modified methods are compatible with and attempt to update the procedures used for ground water quality assessment models such as the Erosion-Productivity Impact Calculator (EPIC) model. On the other hand, our estimations of N loading make use of derived equations from Boisvert, *et al.* (1997) that relate nitrate loading from corn production to soil characteristics, weather, crop rotations and fertilizer application methods using nitrate runoff and leachate data generated from GLEAMS for specific New York soils.

We incorporate solutions to our nonlinear programming model into the abstractions of the known relationships between nutrient application, land vegetative cover and soil characteristics, weather, and nutrient loading. Land nutrient application rates in turn also differ in our model by crops grown on land owned or rented by the farm (i.e., corn grain, corn silage, alfalfa or orchard grass); the position of the current (corn) crop in the rotation (i.e., whether corn follows other corn, alfalfa or orchard grass in rotations); classification of the land based on crop productivity (i.e., low; medium, or high); and levels of soil test phosphorus (i.e., low; medium or high). We account for these field-level differences in cropping and nutrient management, in our estimation of the phosphorus and nitrogen runoff from the dairy farm. Due to limitations in our empirical data, we estimate phosphorus and nitrate loss in runoff for corn fields only, thereby placing a conservative limit on our estimates.

Phosphorus Runoff

Many studies have attempted to assess field level losses of phosphorus from agricultural land based on soil characteristics and applied manure, compost and fertilizers (see for example, Davis, *et al*., 2005; Sharpley and Moyer, 2000; Sharpley, *et al*., 2001; and Vadas, *et al*., 2008). The more recent studies make use of some notion of P runoff indexes that account for differences in nutrient management practices, soil characteristics and geographical and agro-climatic conditions, and rank the potential for P loss from agricultural fields. These methods of classifying P loss risks have gained popularity such that several U.S. states have adopted a P index (PI) as their primary risk assessment tool for ranking the vulnerability of fields to P loss. Sharpley, *et al*., (2003) for example, reports that 47 states used the PI approach by 2003 and had mostly developed the index to suit local conditions and policy. A drawback to the use of P indexes is that most of them do not explicitly quantify P loss, posing a challenge to P loss reduction planning. Process-based simulation models address these concerns in that they can quantify field-level losses of P in runoff. These models are however considered difficult to use for routine management purposes and may have excessive field-specific data requirements (Vadas, *et al*., 2009)

New techniques developed by Vadas, *et al*., (2009) offer an improvement on the indexation methods without requiring the expertise or additional data associated with the process-based models. Their methods, which are compliant for use with existing tools such as EPIC, were validated against data from several independent published field studies, and are useful for predicting annual dissolved P in runoff from surface-applied manure and fertilizers. Their techniques incorporate manure and fertilizer P runoff equations in the development of a P loss quantification tool to estimate total dissolved and sediment P in runoff from soil, eroded sediment, manure and fertilizer. We follow this general method in our estimation of phosphorus loss in runoff. However, the focus of our study on the marginal changes in nutrient loadings attributable only to differences in field nutrient management allows us to ignore without consequence, the determination of P runoff losses that are a function of the soil characteristics or erosion factors.[10] We thus restrict our adoption of the models by Vadas, *et al*., (2009) to the estimation of P loss in runoff from manure and fertilizers.

We incorporate our solutions from the nonlinear programming model that represent the optimal nutrient management decisions of the representative farm into abstractions of the relationships between land nutrient application, weather incidences and environmental loading. We make use of available data on soil characteristics and weather events representative of agricultural soils and regions in New York State.

Estimation of P Runoff from Manure

For our modeling purposes, dissolved P in runoff from applied manure is estimated as in equation (1.1):

$$ROP_{man} = 0.4 * PR_{man} * PDF_{man} * \left(RO/PPT\right) \qquad (1.1)$$

where ROP_{man} is the amount of dissolved phosphorus lost in runoff from manure in a rainstorm event (lbs/ac.); PR_{man} is P released from applied manure (lbs/ac.) and is the amount of dissolved P leached out of manure particles by precipitation during an event; PDF_{man} is a factor for manure application that distributes released P between runoff and infiltration, and ranges between 0.0 and 1.0; *RO* is the precipitation runoff (in.) from the relevant storm incidence; and *PPT* is the measured amount of precipitation from the storm event (in.). PR_{man} is further defined as P available for

[10] It is reasonable to assume that the land nutrient management factors are the only relevant variables from the no-policy to the nutrient regulations scenario. Soil characteristics such as initial soil nutrient status and topography are constant.

runoff from the applied manure in water extractable phosphorus (WEP) and non-WEP forms. All P that is in non-WEP form at the time of manure application is unavailable for runoff at that time. According to Vadas, *et al*. (2009), 40 percent of applied manure WEP is available for direct loss to runoff from applied liquid manures and 10 percent of non-WEP becomes mineralized and available through the year. In our model, the estimates of total P produced in manure for the various fed rations come from the CPM-Dairy program output and are for all manure P that is available for plant uptake. The data do not distinguish manure WEP from non-WEP and we assume in our model that 40 percent of total manure P is available for direct runoff in a storm event.

The manure P distribution factor is determined as follows in equation (1.2):

$$PDF_{man} = \left(RO/PPT\right)^{0.225} \tag{1.2}$$

where PDF_{man} is the manure distribution factor and RO and PPT are the runoff and precipitation variables, respectively, as defined above in equation (1.1). We adopt the curve number method developed by the Natural Resources Conservation Service (NRCS) to predict RO, the amount of precipitation runoff from fields (NRCS, 2003b). The curve number method uses empirically-determined mathematical relationships and appropriate values read off a curve number chart in the prediction of runoff. Its suitability for use in models that estimate P-runoff from variable source areas has been questioned (see Easton, et al., 2007). Notwithstanding, the results of our study do not account for spatial distribution of P runoff within the context of the cropland available to the dairy farm, thus making the curve number approach suitable for our purpose.

Our estimation of the field runoff from precipitation follows equation (1.3):

$$RO = \left(PPT - 0.2 \cdot S\right)^2 / \left(PPT + 0.8 \cdot S\right) \tag{1.3}$$

where *RO* is the depth of runoff from the cornfields (in.) and is measured as rainfall in excess of the soil's capacity for infiltration. It depends on the intensity of rainfall as well as on such field characteristics as land use type, vegetative cover, and soil hydrologic group. *PPT* is the observed depth of rainfall for a single storm incidence in inches as earlier defined; and *S* is the depth (in inches) of effective available storage on the fields.

Further, *S* is determined following equation (1.4):

$$S = (1000/CN) - 10 \qquad (1.4)$$

where *S* is the effective storage capacity of the field and *CN* is the curve number. The *CN* is read off the appropriate NRCS charts (NRCS, 2003b). It varies by soil hydrologic group, as well as by land use type. The latter distinction does not occur in our model as all of the fields for which we calculate P runoff loss are agricultural plots with row (corn) crops. However, following available soil survey data for the New York agricultural production region that our representative farm model captures, we identify soil hydrologic groups A, B, and C and the proportions of croplands on the representative farm that belong to each of these groups (see Table 4 in Boisvert, et al., 1997). Our estimation of the P runoff thus accounts for the soil hydrologic groups.

Estimation of P Runoff from Commercial Fertilizers

The estimation of phosphorus runoff from fertilizers applied is similar to that for P loss from manure in equations (1.1) through (1.4), with some modifications. Estimation of the amount of dissolved P in runoff from applied fertilizers follows equation (1.5):

$$ROP_{fer} = PR_{fer} * PDF_{fer} * \left(RO/PPT\right) \tag{1.5}$$

where ROP_{fer} is the amount of dissolved phosphorus lost in runoff from fertilizer in a rainstorm event (lbs/ac.); PR_{fer} is P released from applied fertilizer (lbs/ac.) and is the amount of dissolved P leached out of fertilizer by precipitation during an event. It includes all of the P applied in fertilizer form. PDF_{fer} is a fertilizer distribution factor which estimation is defined shortly; *RO* and *PPT* are runoff and precipitation (in.) as defined above.

The fertilizer P distribution factor is determined as in equation (1.6):

$$PDF_{fer} = 0.034 * \exp\left[3.4 * \left(RO/PPT\right)\right] \tag{1.6}$$

where PDF_{fer} is the fertilizer distribution factor and lies between 0.0 and 1.0; and *RO* and *PPT* are the runoff and precipitation variables as defined. RO is as determined in equation (1.3).

Incorporating P Runoff into the NLP Model

Solutions to our NLP model enter into the equations for estimating P loss in runoff as values for the amount of P available for release from applied manure and fertilizers (i.e., PR_{man} and PR_{fer} in the P runoff equations). Since fertilizer and manure application rates potentially differ by cropping activity (i.e., by land capability class, crops grown, position of cropping in rotations and in the CAFO regulations case, restrictions on land nutrient application), we necessarily apply equations (1.1) through (1.6) to each cropping activity that comes into the NLP solution. Further, we evaluate the equations for each of three particular measures of rainfall in the year and for 30 years of weather observations. The total P runoff for any cropping activity in any given year is calculated as the sum of residual P associated with manure and with fertilizer application and accumulates P lost to runoff through the storm incidences occurring in that year.

Total annual P runoff for individual cropping activities cumulatively sum up the runoff P associated with each of the storm events. This is such that P leached out of applied manure or fertilizer in a first (second) storm incidence is no longer available for loss through runoff during a second (third) storm event. In particular, equations (1.1) and (1.5) can be re-written as in equations (1.7) and 1.8):

$$ROP_{man}^{t} = 0.4 * (PR_{man}^{t} - PR_{man}^{t-1}) * PDF_{man} * (RO/PPT) \qquad (1.7)$$

$$ROP_{fer}^{t} = (PR_{fer}^{t} - PR_{fer}^{t-1}) * PDF_{fer} * (RO/PPT) \qquad (1.8)$$

where ROP_{man}, ROP_{fer}, PR_{man}, PR_{fer}, PDF_{man}, PDF_{fer}, RO and PPT are defined as in equations (1) through (6). The superscript t represents the three rainfall observations that are relevant to our estimation [i.e., t = 1, 2 and 3; the measures of rainfall observed in the 14 days after planting, fertilizer application, and harvesting, respectively (in.)].

We determine the cumulative sum of P runoff for a single cropping activity, from all weather incidences within the year or season as in equation (1.9):

$$PRO_{j} = \sum_{t=1}^{3} ROP_{man}^{tj} + \sum_{t=1}^{3} ROP_{fer}^{tj} \qquad j= 1,\ldots, J \qquad (1.9)$$

where PRO_j is the amount of dissolved phosphorus lost in runoff (lbs/ac.) from manure and/or fertilizer application associated with cropping activity j over all storm events.

Total P runoff for all of the grown corn acres is then determined as:

$$TPRO = \sum_{j=1}^{J} \left(PRO_j * Ac_j \right) \qquad (1.10)$$

where *TRPO* is the amount of P runoff from manure and fertilizer application on all cropped corn acres (lbs). PRO_j is the amount of dissolved phosphorus lost in runoff from manure and/or fertilizer application associated with cropping activity *j* (lbs/ac.); and Ac_j is the relevant number of crop acres (ac.).

Nitrate Runoff and Leaching

To determine the effects of new nutrient restrictions on nitrogen loading on our representative dairy establishment, we predict potential levels of N runoff and leaching associated with the changes in land application of manure and fertilizer on corn acres. To do this, we make use of empirical techniques developed in Boisvert, et al. (1997). In that work, estimates of N runoff and leachate were obtained for different length corn rotations and fertilizer application rates using GLEAMS for 105 New York soils. The resulting data were then used to estimate recursively equations relating nitrate runoff and leaching from corn production to soil characteristics, weather, rotations and fertilizer application. The relationships between nitrate runoff and leaching estimates and soil characteristics, weather and cropping practices in the agricultural production regions of New York were represented in translog functional form. The nutrient loading function is stated in its general form as:

$$\ln Y = \ln e_0 + \sum_{h=1}^{H} d_h D_h + \sum_{k=1}^{G} e_k \ln W_k + 1/2 \sum_{k=1}^{G} \sum_{l=1}^{G} f_{kl} \ln W_k W_l \qquad (1.11)$$

where Y is either nitrate runoff or leaching; d, e and f are the relevant parameters of the equation, D_h are dummy variables that take on the value of one if a soil is in hydrologic group h and zero otherwise; and W_k is the k^{th} of G variables representing soil characteristics, cropping practices and weather factors. The set of recursive equations for estimating nitrate runoff and leaching are presented in detail in Appendix 1.C.

Nitrate runoff appears as an explanatory variable in the leaching equations to account for the fact that increased surface runoff leaves less N to leach out from the soil. Dummy variables account for differences in the hydrologic groups of the soils A, B and C. Soils in group C have potential for higher runoff as they are heavier and have greater slope.

In evaluating programming model solutions, we allow to change in the nitrate loading equations only the values for those variables that are directly related to soil nutrient management – i.e., manure and fertilizer application. The means and regression coefficients for all other variables are assumed constant. Field characteristics such as the slope, soil horizon depth, N mineralization rates, organic matter content and erodibility are assumed to take on the mean values for the region and do not change with cropping patterns.

We allow for the effects of variation in weather by evaluating the regression equations for a sample of historical weather observations. We keep the nutrient management variables constant for any single weather observation, thereby restricting variations in weather across the fields. Our sample of weather observations consists of actual weather data for New York State counties (Boisvert, et al., 1997).

Results and Discussions

We present results that indicate the direct implications of the new nutrient restrictions on CAFOs in New York State. First, we present the results for a base scenario in which there are no restrictions on manure and fertilizer application for the representative dairy farm. Next, we look at the implications for the base case of changes in the prices and availability of DDGS. We then investigate the policy case in which nutrient restrictions are applied.

Our analysis uses average prices for (year) 2008 as the relevant starting coefficients in the model. It is increasingly clear however, that the elevated feed prices experienced early in 2008 may not be sustainable in the long term. The relative prices of low-cost alternatives for feed ingredients - such as DDGS - could continue to change. We thus first conduct a parametric analysis of feed prices, allowing the relative price of DDGS to change so that we investigate the effects of changes in relative feed prices on the dairy management response. The dairy farm responses to the prices of feed ingredients have implications for the nutrient content in manure, and for farm nutrient management. They also have implications for the extent to which CAFOs can respond to feed price-related changes in agricultural markets in the face of new restrictions on land nutrient application.

Our modeling of the nutrient regulations sets yield expectations consistent with agriculture in the production region and limit land application of manure and fertilizer nutrients to agronomic uptake rates. To determine the implications of the new state-specific nutrient standards, we compare the solutions to the NLP model for the scenario that assumes restrictions to N and P application on field crops to that which does not include nutrient use limitations in the management decisions. To determine other market effects on the management response to nutrient policy, we systematically vary the costs associated with off-site transportation of animal manure to account for the increased need for manure disposal. The manure disposal costs encompass the volumes of manure that need to be shipped to off-farm sites as well as the distances travelled to find suitable land. Throughout, we link the indicators of nutrient management adjustments generated from our NLP optimization models – for example, the rates of fertilizer and manure nutrients applied to the fields – to sets of equations that estimate phosphorus loss in runoff and nutrient runoff and leaching from acres growing corn. We track the changes of the farm income of the representative animal feeding operation under the different policy and market scenarios.

The Base Scenario

At 2008 average prices for production inputs and outputs, 250 milk cows, 250 dry cows, and 195 replacement heifers are raised on the representative farm. The milking cows are fed a primarily corn silage-base ration of 10 percent dry matter content of 8 percent fat DDGS; 10 percent of the dry matter fed to dry cows is 8 percent fat DDGS while heifers are fed 13 percent dry matter of 8 percent fat DDGS.

In Table 1.5, we summarize major revenues and costs associated with the base simulation of the representative dairy farm management decisions where no restrictions on land nutrient application are in effect. In this base case, the total receipts to the farm per cow are $4,360. About 67 percent of this gross farm income is expended in production (i.e. $2,929/cow), with feed purchases accounting for the largest share of production costs at $1,108 per cow. Milk sales are expectedly the biggest income source and are 86 percent of all farm proceeds. Manure and nutrient management costs are a small fraction of the total production costs .[11] As seen in Table 1.5, nutrient management, although still a relatively small factor of the

[11] Manure and nutrient management costs include the cost of spreading manure on land, purchasing and spreading fertilizers; and in the policy case, disposal of excess manure off-site.

production outlay at $132 per cow per year is a more important cost component for the model simulation that includes restrictions on land nutrient application. We however leave to a later section the discussions on revenues and costs associated with the nutrient policy scenario. We instead focus here on how the programming solutions to the base scenario change as DDGS pricing is adjusted.

Table 1.5: Net annual revenues, receipts and costs:
Base and **Policy** scenarios

	Base Solution (No Policy)	Policy Solution (Nutrient Standards)
	$/cow	
Net annual revenue	1,432	1,388
Total receipts	4,360	4,360
Milk	3,744	3,744
Crop sales	340	340
Livestock sales	276	276
Total Costs	2,928	2,972
Feed	1,108	1,108
Labor	661	650
Crop production[1]	362	362
Other production costs[2]	720	720
Nutrient management	75	132
Manure spreading	44	26
Offsite disposal[3]	0	48
P fertilizer purchases	12	18
N fertilizer purchases	19	19
K fertilizer purchases[4]	0	21

[1] Custom lime, seeds, herbicides and soil testing.
[2] Livestock production (utilities, veterinary, supplies, repairs and maintenance).
[3] Manure disposal costs assumed to be $4/ton.
[4] The model assumes that up to 4 lbs/ac of potassium is available in manure. This amount is sufficient to meet crop demands. Fertilizer K purchases are likely only required on acres where manure is not spread.

We examine modeling programming solutions that are associated with DDGS prices for relevant DDGS-to-corn price ratios as presented in Table 1.6. We examine 7 sets of our programming solutions that are associated with relative DDGS prices. The price ratios range from more than twice the (2008) per ton cost of corn grain (i.e. a DDGS-to-corn price ratio of 2.04:1) to less than one half of the same price (i.e. 0.45:1). Six of the solution sets are the programming solutions obtained when the optimal dairy management solution changes in response to the change in DDGS prices. The solution set representing the biofuels byproduct feed-to-corn ratio of 0.60-to-1 is for 2008 prices of DDGS (see Table 1.6). The 2008 price for corn is $234.7 per ton DM. As DDGS prices are allowed to change relative to other feed prices, the combined demand for (8 and 12% fat-) DDGS also changes. While the optimal numbers of animals do not change as the relative prices and utilization of other feed ingredients to DDGS changes, the amounts fed of the biofuels byproduct change. In general, a greater proportion of the animals are fed with rations that include DDGS as its relative price falls. For a DDGS-to-corn price ratio of 2.04:1, no DDG is fed. However, when the price ratio falls to 0.45:1, all of the animals are fed DDGS in rations, and the low-cost feed ingredient is up to 17% of the total mixed ration (not shown in table).

As more DDGS is fed, the total volume of manure produced does not change by any significant amount. However, the amounts of nitrogen and phosphorus available in the manure produced increase. The levels of nitrogen and phosphorus in rations that include DDGS tend to be higher than in those without the distillers' by-products. As shown in Table 1.6, 71 pounds of manure phosphorus are produced per cow per year when no DDGS is fed, compared to 84 pounds of P produced per cow when the DDGS-to-corn price ratio is 0.45:1; i.e., where all of the animals are fed DDGS in rations.

Table 1.6: Feeding, nutrient management and environmental loading as DDGS prices change: **Base** scenario

Price ratio[1]	2.04	1.91	1.46	0.84	0.78	0.60[1]	0.45
Net revenue ($/cow)	1,287	1,290	1,309	1,361	1,382	1,432	1,452
Rations fed[2] (% cows):							
CowCS	100	100	100	17	0	0	0
CowCS1210	0	0	0	83	100	100	0
CowALF0820	0	0	0	0	0	0	100
DCow	100	0	0	0	0	0	0
DCow8	0	100	100	100	100	100	100
Hef	100	100	0	0	0	0	0
Hef8	0	0	100	100	100	100	100
Manure produced (tons)	7300.0	7300.0	7300.0	7325.4	7330.5	7330.5	7475.4
P in manure (lbs/cow/yr)	71.27	72.89	77.23	77.32	77.34	77.34	84.74
N in manure (lbs/cow/yr)	179.18	177.36	177.00	182.11	183.13	183.13	210.84
P application on fields[3] (lbs/ac)	39.99	40.05	39.94	40.02	40.03	40.03	39.95
Manure P (%)	77	80	81	89	91	91	96
N application on fields[3] (lbs/ac)	97.36	97.96	94.00	103.86	106.11	106.11	115.42
Manure N (%)	79	80	79	81	81	81	83
P runoff (lbs/ac): *Mean*	4.89	5.04	5.06	5.43	5.50	5.50	5.72
P runoff (lbs/ac): *Maximum*	12.15	12.33	12.36	12.82	12.92	12.92	13.19
P runoff (lbs/ac): *Std Deviation*	3.58	3.67	3.68	3.90	3.95	3.95	4.08
N loading (lbs/ac): *Mean*	6.88	6.95	6.48	7.32	7.52	7.52	8.19
N loading (lbs/ac): *Maximum*	15.55	15.89	14.81	16.82	17.28	17.28	19.14
N loading (lbs/ac): *Std Deviation*	3.14	3.23	3.01	3.43	3.52	3.52	3.94

[1] Ratio of the price of DDGS to the price of corn grain on a per ton basis (dry matter). To compute the DDGS price, multiply ratio by $234.7/ton. The price ratio of DDGS-to-corn in 2008 is 0.60:1.
[2] Ration headings are formatted by primary forage base, DDGS fat percentage, and percentage of DDGS fed on a dry matter basis, respectively; e.g., CS0810 = primary corn silage forage base, 8% fat DDGS, and 10% DDGS fed.
[3] Nutrient applications on corn acres. N application includes starter nitrogen.

In the case of nitrogen, 180 pounds are produced in manure per cow for the DDGS-to-corn price ratio of 2:04:1, compared with 210 pounds for the 0.45:1 price ratio. As more P is produced in manure, more of the crop P requirement is met using manure and smaller amounts of phosphorus need be purchased as commercial fertilizer (see Table 1.6). Phosphorus applied on corn fields from manure (as a percent of total P applied) goes up from 77 to 96 percent, as the relative cost of DDGS declines. The additional savings on fertilizer purchases lead to an increase in the farm's net revenue. However, the higher rates of nutrient applications from manure lead to more phosphorus and nitrate being available for runoff and leaching to the environment.

According to our model, field N and P are applied from commercial and manure sources at 97.36 and 40 pounds/acre, respectively, when the DDGS to corn ratio is 2.04: 1. Nitrogen loading from the cornfields is 6.88 pounds/acre on average at this price level while P loading to the environment is 4.89 pounds/acre on average. On the other hand, mean N and P runoff and leaching at the lowest DDGS-to-corn ratio that we examine (0.45:1) are 7.52 and 5.5 pounds/acre respectively, representing 9 percent and 11 percent increases in environmental loading.

No manure is shipped off from the dairy farm under the base (no policy) scenario.

The Policy Scenario

The dairy management follows the same feeding regime in the nutrient policy scenario as in the no-policy case. As the relative price of DDGS falls, more of the alternative feed ingredient is fed in the dairy ration. However, manure produced in excess of the farm's crop requirements must be shipped off the farm when the new regulations are in effect, so that net revenues fall with the increased costs of off-farm manure disposal. We report the programming solutions for the base and policy scenarios for a given set of feed prices and estimates of the unit costs of off-site manure disposal in Table 1.7. The off-site disposal costs implicitly represent the distances that dairy operators must travel to find suitable land for manure disposal. These distances (and manure costs) would increase substantially if the representative farm is in a region with a high concentration of similar operations such that the volume of manure nutrients produced outstrips the absorptive capacity of nearby farmlands suitable for disposal. When the costs associated with transporting manure off the farm to other (net receiving) farms or collection centers are increased systematically, we are able to observe the critical points at which current farm operations are no longer optimal. We also determine changes in the dairy operation that must accompany the rising costs, for the farm feeding, cropping and whole-farm nutrient management plan to become optimal. With the new nutrient standards in effect, the representative dairy farm in our model can respond to prohibitive costs for off-farm manure disposal by reducing the herd size to effectively cut back on manure production. This nutrient management strategy is unlikely to be observed in practice so we restrict our discussion of the results to the feasible range of off-site disposal costs where the animal feeding establishments keep their dairy operations in business.

Using 2008 estimates of $4 per ton for manure disposal, our analysis shows only minimal changes in the farm animal production and feeding activities from the base to the policy simulations.[12] The herd size and the composition of the total mixed ration fed to milking cows, dry cows or heifers do not change. Farm income from milk and livestock sales are also essentially the same (see Table 1.5). Expected net revenues however fall from $1,430 per cow to $1,388 per cow. While the overall crop

[12] Our estimates of manure disposal costs in 2008 compare with calculations from Harrigan (2001) and Hadrich, *et al*., (2008) that place manure disposal costs between $2.2/ton and $4.4/ton.

production costs (not including manure and fertilizer application or manure disposal) do not change, other factors associated with cropping do change. In particular, the number of labor hours needed for spreading manure on crop acres falls, as well as the acreages of farmland devoted to corn. The most important changes that we find are related to crop nutrient management and environmental nutrient loading.

Nutrient Management and Off-Farm Manure Disposal

As outlined in the previous sections, all of the manure that is produced is applied on the land in the base representation of the dairy farm where the new nutrient use restrictions are not followed. This optimal management decision would not change in response to changing costs of disposing of manure off-site. On the other hand, some of the manure produced is shipped off the farm and increasing off-farm shipping costs have major implications in the policy case. In Table 1.7, we compare manure and fertilizer application on the representative dairy operation for the base scenario and 8 policy scenarios representing increasing costs for off-site manure disposal. Manure disposal costs start out at $2 per ton (14 miles roundtrip if we assume $0.14 per ton-mile) and rise in $2 increments to $16/ton (114 miles roundtrip).[13] The travel distances implied in our analysis fall within the limit of the maximum distances (170 miles) for which manure-exporting farms could receive subsidies under a poultry litter transportation program as modeled for Virginia in Pelletier, et al. (2001).

In our evaluation of the base and policy scenarios, we find that nitrogen is applied as manure and fertilizer N at 106 lbs/acre on average in the base case. This application rate is significantly reduced in the policy scenario, to 68 lbs/acre.

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[13] Information on per ton-mile estimates for dairy manure follow Pelletier, *et al*. (2001); Feinerman, *et al*. (2004) and USDA indices of agricultural prices paid.

Table 1.7: Manure and fertilizer management and environmental loading with increasing costs for off-site manure disposal: **Base** and **Policy** scenarios

Disposal Costs $/ton	Base Scenario	2	4[1]	6	8	10	12	14	16
Net revenue ($/cow)	1,432	1,412	1,388	1,364	1,341	1,319	1,297	1,276	1,255
Manure produced (tons):	7330	7330	7330	7330	7330	7330	7330	7330	7330
Disposed off-farm (%)	0	41	41	40	40	36	36	36	36
Nutrient management on corn:									
P application[2] (lbs/ac)	40	31	31	27	27	15	15	15	15
Manure P (%)	91	64	64	68	68	88	88	88	88
N application[2] (lbs/ac)	106	68	68	68	68	68	68	68	68
Manure N (%)	81	70	70	64	64	45	45	45	45
P runoff from fields (lbs/ac)									
Mean	5.5	3.4	3.4	3.0	3.0	2.0	2.0	2.0	2.0
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	12.9	8.7	8.7	7.9	7.9	4.7	4.7	4.7	4.7
Std. Deviation	4.0	2.5	2.5	2.3	2.3	1.4	1.4	1.4	1.4
N runoff and leaching from fields (lbs/ac)									
Mean	7.5	4.5	4.5	4.5	4.5	4.4	4.4	4.4	4.4
Minimum	3.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Maximum	17.3	9.6	9.6	9.5	9.5	9.3	9.3	9.3	9.3
Std Deviation	3.5	1.9	1.9	1.8	1.8	1.8	1.8	1.8	1.8

[1] The relevant policy scenario for comparison with the base case is the model simulation when off-site manure disposal is $4/ton.
[2] Nutrient applications on corn acres. N applications include starter nitrogen.

Similarly, P application rates are 40 lbs/acre and 31 lbs/acre on average, respectively, for the base and nutrient standards scenarios. Following the reductions in P and N applications, environmental nutrient loading risks fall on average. We leave the detailed discussion on the implications of the policy for environmental nutrient losses to a later section.

Of the N that is applied to the fields, 81 percent is from manure in the base case while 70 percent is from manure in the policy case. About 91 percent of applied P is from manure in the base case compared with 64 percent under the simulation of the new nutrient restrictions. These results show that the representative farm purchases relatively more of commercial fertilizers under the policy than in the no-policy case. Further, the representative farm purchases more than 6 pounds per acre of fertilizer P for corn cropping under the nutrient restriction scenario. More than twice that amount is disposed of off-farm as manure nutrients (not shown in Table).

Off-site Manure Disposal Costs

From Table 1.7 we note that net incomes fall as the manure disposal costs go up. The expected net revenue is $1,412 per cow when manure disposal cost is $2/ton and $1,255/cow when the cost increases to $16 per ton. This represents an 11 percent drop in expected net farm incomes over the relevant range of manure disposal costs. To mitigate the effects of the increasing costs and associated losses to farm income, less of the manure produced is taken off the farm as the off-farm manure transportation costs (distances) increase in the model. When the off-site disposal cost goes up from $2 per ton to $16 per ton, off-farm manure disposal drops from 41 percent to 36 percent of the total volume of manure produced.

We find that nitrogen application per acre does not change by very much across the policy simulations when off-site manure disposal costs are increased while

P applications on the other hand are noticeably reduced. Mean phosphorus application falls by 42 percent over the range of manure disposal costs that we examine. Underlying the changes in nutrient application are cropping and land nutrient management adjustments that the representative dairy farm makes to accommodate the need to spread more manure on (ship less manure off) the farm.

Adjustments to Cropping and Nutrient Management

More manure may be spread on land growing alfalfa than is needed to meet nitrogen requirements in the model simulation of the environmental regulations.[14] We find that the representative farm manager takes advantage of this manure management option to compensate for increased restrictions on using manure to supply nutrients to growing corn. While the total acreages are equivalent for corn and alfalfa under the alternative policy scenarios (i.e., base versus nutrient restrictions), the proportion of corn or alfalfa land that manure is spread on changes. We find that while nutrients in manure form are applied to all of the corn acres in the base case, only 235 of the 310 acres (i.e., 76 percent) of land in corn receive manure in the nutrient standards case. Manure application in the policy case covers 100 percent (up from 90 percent) of cropped alfalfa acres (see Table 1.8). The optimal nutrient management option in the base case is to apply manure at 13.8 tons/acre on corn land, and 9.8 tons/acre on alfalfa (Table 1.9). These application rates allow for application of N and P above the levels required for optimal production. With the nutrient policy in effect, the average rate of manure application falls to 6.3 tons/acre on corn and 8.3 tons/acre on alfalfa. The representative farm manager similarly makes adjustments to cropping and land

[14] Application of other sources of nitrogen to alfalfa is unnecessary since it typically meets all of its requirements through biological fixation of N. Its agronomic characteristics however ensure that alfalfa may receive up to 10 tons per acre of manure and still conform to nutrient management plans in New York State (Ketterings et. al., 2006).

nutrient management to accommodate increasing off-site manure disposal costs. These adjustments underlie the reduced P applications reported in the previous section for increased off-farm manure disposal costs (i.e., in Table 1.7).

Table 1.8: Manure and nutrient management on corn and alfalfa acres:
Base and **Policy** scenarios

	Base Solution (No Policy)	Policy Solution (Nutrient Standards)[1]
Manure management:		
Manure produced (tons)	7,330	7,330
shipped off-farm (%)	0	41
Corn grain and silage cropping:		
Cropped land (acres)	310	310
With manure application (%)	100	76
With fertilizer N application (%)	0.0	67
With fertilizer P application (%)	20	17
Alfalfa hay cropping:		
Cropped land (acres)	310	310
With manure application (%)	89	100
With fertilizer N application (%)	0	0
With fertilizer P application (%)	77	0

[1] The relevant policy scenario for comparison with the base case is the model simulation when off-site manure disposal is $4/ton.

The dairy farm essentially switches corn from low soil test P land (i.e., requiring 40 lbs/ac of P application) to medium soil test P soils (i.e., with no more than 15 lbs/ac P requirements). On the other hand, more alfalfa is grown on low P soils to meet the higher allowed P application rates while allowing for the over application of nitrogen nutrients from manure (not shown in tables). The crop production and nutrient management adjustments to the new nutrient standards are important from an environmental nutrient loading perspective.

Table 1.9: Manure and fertilizer nutrient applications:
Base and **Policy** scenarios

	Base Solutions (No Policy)	Policy Solutions (Nutrient Standards)[1]
Corn grain and silage:		
Soil nutrient application (per acre):		
Manure (tons)	13.8	6.3
N in manure (lbs)	86.1	39.0
P in manure (lbs)	36.4	16.5
N in fertilizer[2] (lbs)	20.0	28.5
P in fertilizer (lbs)	3.7	6.47
Alfalfa hay:		
Soil nutrient application (per acre):		
Manure (tons)	9.9	8.3
N in manure (lbs)	61.7	51.6
P in manure (lbs)	26.1	21.8
N in fertilizer (lbs)	0.0	0.0
P in fertilizer (lbs)	4.0	0.0

[1] The relevant policy scenario for comparison with the base case is the model simulation when off-site manure disposal is $4/ton.
[2] Includes purchase of 20 lbs/ac of pre-sidedress nitrogen.

Nutrient Loading to the Environment

To estimate environmental loading of P and N, we apply equations predicting phosphorus runoff and nitrogen leaching and runoff from the corn fields to manure and fertilizer nitrogen application rates from our solutions to the representative farm programming model.[15] We compare environmental nutrient loading for the base and nutrient policy cases. The base case simulates 2008 prices for all production inputs and outputs, including prices of low cost feed ingredients. The relevant policy scenario is where off-site manure transportation costs reflect costs of manure disposal in 2008.

[15] Nitrogen runoff and leaching from alfalfa cropping is assumed negligible and is not estimated.

Estimations of phosphorus and nitrate loss in runoff and leaching are derived for soils of hydrologic groups A, B and C so that weighted average loadings are calculated for the representative dairy operation following the empirical distribution of soils in the relevant agricultural production region of New York (Boisvert, *et al*., 1997).

Nutrient loading is estimated for each of the 30 years of weather for which historical data are available. The nutrient loading estimations we derive do not necessarily predict nutrient leaching and runoff over time but represent a sample of 30 observations from the underlying distributions of runoff and leaching. For the various crop production activities, we assume that the soil characteristics do not change such that it is possible to isolate variations in P and N runoff and leaching that are due to differences in weather and to differences in field nutrient management.

Phosphorus Loss in Runoff

To examine the effect on P loading of the new nutrient restrictions, we rank by the severity of the historical precipitation incidences (i.e., from low to high) our estimates of P loss in run-off for the 30 years for which we have precipitation data. This is shown in Figure 1.2 for the base and policy scenarios. The mean P loss in runoff is 5.5 pounds/acre in the base case, and 3.4 pounds/acre under the nutrient regulations, representing a 38 percent reduction in P loading per acre with the policy. The maximum possible P runoff, given our sample of weather data, is 12.9 pounds/acre in the base case, with simulation of the nutrient policy reducing this measure of P loading by 30 percent. While these results suggest that the new nutrient standards could reduce P loading on average, they also indicate that significant risks of P runoff could remain for severe storm events.

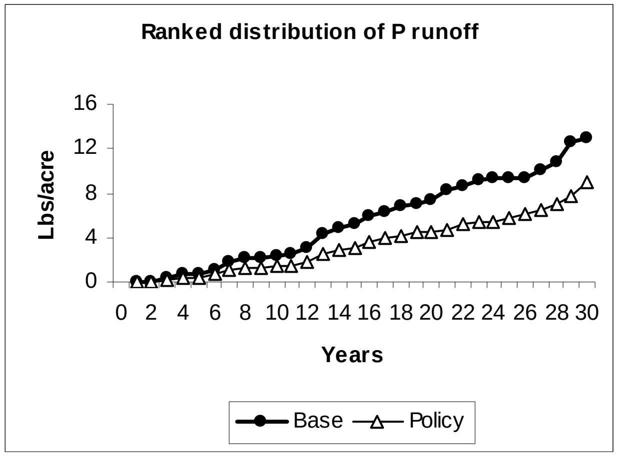

Figure 1.2. Phosphorus loss in runoff for the **Base** and **Policy** scenarios

Nitrate Runoff and Leaching

As with P loading, we rank our estimations of the mean nitrate loading for the base and policy scenarios for corn acres grown and for the historical weather data. This ranking is shown in Figure 1.3 for the base and policy scenarios. Expectedly, limiting land nutrient application to the agronomic soil uptake rates leads to reduced amounts of nitrate loss in runoff and leaching throughout.

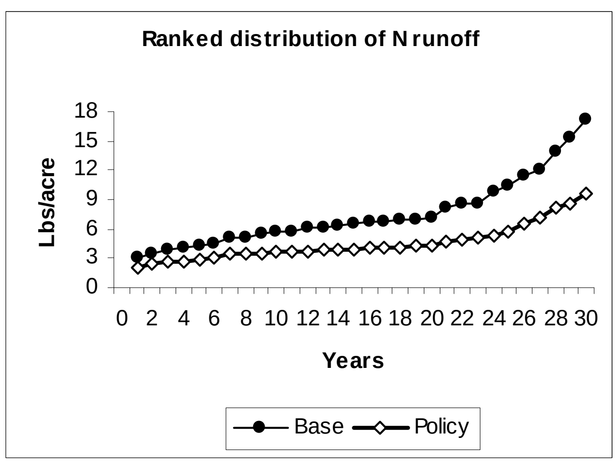

Figure 1.3. Nitrate runoff and leaching under the **Base** and **Policy** scenarios

The mean nitrate loading for the base scenario is 7.5 pounds/acre, while the maximum level of runoff and leaching associated with the 30 years of weather data is 17.3 pounds/acre. Mean nitrate loading for the policy scenario is 4.5 pounds/acre with the estimations ranging from 2.0 to 9.6 pounds/acre/year. However, as with P loading, there may still remain significant risks of nitrate loss to the environment.

Conclusions

To obtain New York State's Pollution Discharge Elimination Permits, large concentrated animal feeding operations in the State must develop comprehensive nutrient management plans (CNMPs). The CNMPs include restrictions on land application of manure and fertilizer nutrients outlined by the appropriate Land Grant University. In this analysis, we assess the potential implications for farm characteristics such as income and for environmental effects such as nutrient loading of implementing the new nutrient standards. To do this, we incorporate salient details of the guidelines for soil nitrogen and phosphorus management in New York State into regional and representative farm mathematical programming models. We analyze important linkages between farm management adjustments and changes in farm income that are due to restrictions on land application of nutrients and to changes in relevant agricultural prices. Our focus on changes in agricultural market prices is informed by the trend of shrinking operating margins experienced by dairy farms in part due to recent volatilities in feed and agricultural markets. In particular, we explore the potential for low-cost feed ingredients in the dairy rations. We also investigate how nutrient management and environmental loading respond to changes in off-site manure disposal costs. Using historical weather data and results from previous research, we are able to associate estimates of nutrient runoff and leaching with the management adjustments deduced from our model solutions.

Our investigation of the potential for low-cost feed ingredients provides some indication that the new restrictions on land application of manure and fertilizer nutrients may not be entirely compatible with the otherwise potential gains to animal feeding operations of incorporating DDGS in feed rations. As DDGS prices fall, more of the bio-energy byproducts are fed, effectively increasing the N and P content in manure, and increasing the risks loading of these nutrients to the environment. This increases the need for off-site manure disposal, with additional cost implications.

Further, we find that the application rates of manure and fertilizer nitrogen on corn fields are reduced with the simulation of the new restrictions on nutrient application. While all of the manure produced by the dairy establishment is applied to the land in the base case, upwards of 40 percent of produced manure is shipped to off-site locations under the nutrient standards scenario. However, although sufficient nutrients are produced in animal manure that could meet the crop requirements of land owned or rented by the representative farm, a substantial amount of these nutrients are not utilized. For example, more than twice the amount of P that is purchased for crop production (3,500 lbs) in the policy case is disposed of in manure shipped off the farm. The requirement for the dairy operation to concurrently fulfill individual restrictions on nitrogen and phosphorus application underlies this result. While N and P are available in manure only in fixed ratios, this ratio could differ significantly from the N-to-P requirement of the soil-crop combination so that there is increased potential for over application of one nutrient in trying to meet the crop requirements for the other. Our results may suggest that policies that by design seek to regulate the application of any single nutrient whose over-application is considered a threat to the immediate environment have at least two major effects. Expenditures on manure application could be reduced while the costs of fertilizer purchases increase. Since the policies in essence require that regulated establishments take account of soil nutrients already available in the soil, they discourage the (otherwise) unnecessary application of manure at rates that exceed the soil nutrient requirements. However, as outlined above, these policies also have the potential to induce regulated CAFOs to purchase *more* rather than less of single nutrient commercial fertilizers.

Simulating the new nutrient application guidelines in our model also indicates some implications for environmental nutrient loading and for farm incomes. Our estimations of nitrate runoff and leaching are reduced on average by more than a third under the nutrient policy scenario. P loading is similarly reduced. However, there may remain significant risks of nutrient loading in extreme weather events. The dairy farm income is expectedly affected by implementation of the nutrient standards, falling by about 6 percent from the base to policy scenarios, and by up to 11 percent for our assumptions on off-site manure disposal costs. Increased purchases of fertilizers account for this decrease in income, with this effect somewhat off-set by such factors as lower requirements for and expenditures on labor.

APPENDIX 1.A

PHOSPHORUS AND NITROGEN LEACHING INDICES

Application of the Phosphorus Index and Nitrogen Leaching Index in Nutrient Management on New York large CAFOs[1]

Index	**Recommended nutrient management strategy**
Step 1:	*Check Phosphorus Runoff Index (PI)*
PI ≥ 100	No manure; no P fertilizers allowed
PI 75 – 99	Manure and/or fertilizers allowed up to crop P-removal
PI 50 – 74	Manure and/or fertilizers allowed up to crop N-removal rates. Implement Best Management Practices (BMPs)[2]
PI < 50	Manure and/or fertilizers allowed up to crop N-removal rates. N management based on Nitrogen Leaching Index
Step II:	*If PI < 50; Check Nitrogen Leaching Index (NLI)*
NLI < 2	BMPs are not required
NLI 2 - 10	Consider implementing BMPs on a case-by-case basis
NLI > 10	Implement BMPs

[1] Adapted from Ketterings, *et al*., 2003a and 2003b.

[2] BMPs include recommendations about optimal rates, methods and timing of manure and fertilizer application. See Ketterings, *et al*., (2003a) for discussion.

APPENDIX 1.B

THE NON LINEAR PROGRAMMING OPTIMIZATION MODEL

Variable and Symbol Definitions:

COW_i = Lactating cows being fed on ration i (i = 1,…,10);

DCOWm = Dry cows being fed on ration m (m = 1,…,5);

HEFn = Heifer replacements being fed on ration n (n = 1,…,5);

MILK = Total milk production, and sold (cwt);

CULLCOW = Sales of cull cows (cwt.);

CULLCALF = Sales of cull calves (cwt.);

OWNLAB = Amount of owner/management labor utilized (hours);

LABOR1 = Amount of level one labor employed (hours);

LABOR2 = Amount of level two labor employed (hours);

BALF = Amount of alfalfa purchased (tons on dry matter basis);

BOG = Amount of orchard grass purchased (tons on dry matter basis);

BCS = Amount of corn silage purchased (tons on dry matter basis);

BCG = Amount of corn grain purchased (tons on dry matter basis);

SALF = Amount of alfalfa sold (tons on dry matter basis);

SOG = Amount of orchard grass sold (tons on dry matter basis);

SCS = Amount of corn silage sold (tons on dry matter basis);

SCG = Amount of corn grain sold (tons on dry matter basis);

BDDGS8 = Amount of DDGS8 purchased (tons on dry matter basis);

BDDGS12 = Amount of DDGS12 purchased (tons on dry matter basis);

BSOY = Amount of Soybean meal purchased (tons on dry matter basis);

$BOPF_q$ = Amount of other minor feed q purchased (tons on dry matter basis) (q = 1,…,9);

$BMAN_{cjk}$ = Manure applied on cropland of land class k and soil P- level j for cropping activity c (tons) (k = 1,…,3; j = 1,…,3 and c = 1,…,8);

TMAN = Manure produced by milk cows, dry cows and heifers (tons);

SMAN = Manure applied as fertilizer on-farm (tons);

DMAN = Manure disposed off-farm (tons);

NMAN = Nitrogen in manure produced (lbs.);

PMAN = Phosphorous in manure produced (lbs.);

NAV = Nitrogen available per ton of manure spread (lbs.);

PAV = Phosphorus available per ton of manure (lbs.);

BSNIT = Amount of Nitrogen fertilizer purchased as Starter (lbs.);

BN_{cjk} = Amount of Nitrogen fertilizer less starter, purchased cropland of land class *k;* Phosphorus-level type *j* and cropping activity *c* (lbs.);

BPH_{cjk} = Amount of phosphorus fertilizer purchased for cropland of land class *k*; Phosphorus-level type *j* and cropping activity *c* (lbs.);

BPOT = Amount of potash fertilizer purchased (lbs.);

BF_f = Amount of fuel of type *f* purchased (gallons) (*f* = diesel and propane);

Acreages under cropping activity:

CS_{jk} = Acres of corn silage following corn (grain or silage) on land class *k* and soil P-level type *j*

CG_{jk} = Acres of corn grain following corn (grain or silage) on land class *k* and soil P-level type *j*;

CSA_{jk} = Acres of corn silage following alfalfa on land class *k* and soil P-level type *j*;

CGA_{jk} = Acres of corn grain following alfalfa on land class *k* and soil P-level type *j*;

$CSOG_{jk}$ = Acres of corn silage following orchard grass on land class *k* and soil P-level type *j*;

$CGOG_{jk}$ = Acres of corn grain following orchard grass on land class *k* and soil P level type *j*;

A_{jk} = Acres of alfalfa on land class *k* and soil P level type *j*; and

OG_{jk} = Acres of orchard grass on land class *k* and soil P level type *j*.

Mathematical Representation of the NLP Model: Equations 1.B.1 – 1.B.33

Objective Function (Maximize Net Revenue):

$$\sum_i -objcow_i COW_i + \sum_m -objdcow_m DCOW_m + \sum_n -objhef_n HEF_n$$
$$-objlOWNLAB - obj1LABOR1 - obj2LABOR2 - objaBALF$$
$$-objogbBOG - objcsbBCS - objcgbBCG - objd8BDDGS8$$
$$-objd12BDDGS12 + \sum_q -objpf_q BOPF_q + \sum_f -objf_f BF_f - objdmanDMAN$$
$$-objdmanSMAN + \sum_k \sum_j \sum_c -objbman_{cjk} BMAN_{cjk} + \sum_k \sum_j -objcs_k CS_{jk}$$
$$+\sum_k \sum_j -objcsa_{jk} CSA_{jk} + \sum_k \sum_j -objcso_{jk} CSOG_{jk} + \sum_k \sum_j -objcg_{jk} CG_{jk}$$
$$+\sum_k \sum_j -objcga_{jk} CGA_{jk} + \sum_k \sum_j -objcgo_{jk} CGOG_{jk} + \sum_k \sum_j -obja_{jk} A_{jk}$$
$$+\sum_k \sum_j -objog_{jk} OG_{jk} + objasSALF + objogsSOG + objcssSCS + objcgsSCG$$
$$+objmilkMILK + objccowCULLCOW + objccalfCULLCALF$$

Constraints:

CowCap: $\sum_i COW_i \leq COWMAX$ (1.B.1)

DryCow: $\sum_i COW_i - \sum_m DCOW_m = 0$ (1.B.2)

CullCow: $\sum_i cwtcowCOW_i - CULLCOW = 0$ (1.B.3)

CullCalf: $\sum_i cwtcalfCOW_i - CULLCALF = 0$ (1.B.4)

Heifer: $\sum_i 0.78COW_i - \sum_n HEF_n \leq 0$ (1.B.5)

Milk: $-\sum_i mcow_i COW_i + MILK \le 0$ (1.B.6)

Labor:

$$\sum_i lcow_i COW_i + \sum_m ldcow_m DCOW_m + \sum_n lhef_n HEF_n - OWNLAB - LABOR1$$

$$- LABOR2 + \sum_k \sum_j lman\,BMAN_{jk} + \sum_j lmanalfBMANALF_j + \sum_k \sum_j lcs_k CS_{jk}$$

$$+ \sum_k \sum_j lcsa_k CSA_{jk} + \sum_k \sum_j lcso_k CSOG_{jk} + \sum_k \sum_j lcg_k CG_{jk} + \sum_k \sum_j lcga_k CGA_{jk}$$

$$+ \sum_k \sum_j lcgo_k CGOG_{jk} + \sum_k \sum_j la_k A_{jk} + \sum_k \sum_j log_k OG_{jk} \le 0 \qquad (1.B.7)$$

Own Labor Available: $OWNLAB \le OWNLABMAX$ (1.B.8)

Labor1 Available: $LABOR1 \le LAB1MAX$ (1.B.9)

Labor2 Available: $LABOR2 \le LAB2MAX$ (1.B.10)

Land: (k = 1,2,3; j = high P, medium P, low P)*

$$CS_{jk} + CSA_{jk} + CSOG_{jk} + CG_{jk} + CGA_{jk} + CGOG_{jk} + A_{jk} + OG_{jk} \le LANDMAX_{jk}$$

(1.B.11)

Alfalfa: (k = 1,2,3; j = high P, medium P, low P)

$$\sum_i acow_i COW_i + \sum_i adcow_m DCOW_m + \sum_n ahef_n HEF_n + SALF - BALF$$

$$-\sum_k \sum_j ayield_k A_{jk} \le 0 \qquad (1.B.12)$$

Orchard Grass: (k = 1,2,3; j = high P, medium P, low P)

$$\sum_i ogcow_i COW_i + \sum_i ogdcow_m DCOW_m + \sum_n oghef_n HEF_n + SOG - BOG$$

$$-\sum_k \sum_j ogyield_k OG_{jk} \le 0 \qquad (1.B.13)$$

Corn Silage: (k = 1,2,3; j = high P, medium P, low P)

$$\sum_i cscow_i COW_i + \sum_i csdcow_m DCOW_m + \sum_n cshef_n HEF_n + SCS - BCS$$

$$-\sum_k \sum_j csyield_k \left(CS_{jk} + CSA_{jk} + CSO_{jk}\right) \le 0 \qquad (1.B.14)$$

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* In the base solution with no nutrient policy, we assume that all of the crop acres are in the low soil P category

Corn Grain:

$$\sum_i cgcow_i COW_i + \sum_m cgdcow_m DCOW_m + \sum_n cghef_n HEF_n + SCG - BCG$$

$$- \sum_k \sum_j cgyield_k \left(CG_{jk} + CGA_{jk} + CGO_{jk} \right) \leq 0 \qquad (1.B.15)$$

DDGS:

$$\sum_i dg8cow_i COW_i + \sum_m dg8dcow_m DCOW_m + \sum_n dg8hef_n HEF_n - BDDGS8 \leq 0$$

$$\sum_i dg12cow_i COW_i + \sum_m dg12dcow_m DCOW_m + \sum_n dg12hef_n HEF_n - BDDGS12 \leq 0$$

(1.B.16)

Soybean Meal:

$$\sum_i sbmcow_i COW_i + \sum_m sbmdcow_m DCOW_m + \sum_n sbmhef_n HEF_n - BSOY \leq 0$$

(1.B.17)

Other Purchased Feeds: (q = 1,…,8)

$$\sum_i pfcow_{iq} COW_i + \sum_m pfdcow_{mq} DCOW_m + \sum_n pfhef_{nq} HEF_n - BPF_q \leq 0$$

(1.B.18)

Fuel: (f = 1, 2)

$$\sum_i fcow_{if} COW_i + \sum_m fdcow_{mf} DCOW_m + \sum_n fhef_{nf} HEF_n + \sum_j fcs_{jkf} CS_{jk}$$

$$+ \sum_j fcsa_{jkf} CSA_{jk} + \sum_j fcsog_{jkf} CSOG_{jk} + \sum_j fcg_{jkf} CG_{jk} + \sum_j fcga_{jkf} CGA_{jk}$$

$$+ \sum_j fcgog_{jkf} CGOG_{jk} + \sum_j fa_{jkf} A_{jk} + \sum_j fog_{jkf} OG_{jk} - BF_f \leq 0 \qquad (1.B.19)$$

Manure Production:

$$- \sum_i cman_i COW_i - \sum_m dcman_m DCOW_m - \sum_n hman_n HEF_n + TMAN = 0 \qquad (1.B.20)$$

Nitrogen in Manure:

$$- \sum_i Ncman_i COW_i - \sum_m Ndcman_m DCOW_m - \sum_n Nhman_n HEF_n + NMAN = 0$$

(1.B.21)

Phosphorus in Manure:

$$-\sum_{i} PHcman_{i} COW_{i} - \sum_{m} PHdcman_{m} DCOW_{m} - \sum_{n} PHhman_{n} HEF_{n} + PMAN = 0 \tag{1.B.22}$$

Inventory of on-farm Manure Application:

$$\sum_{k}\sum_{j}\sum_{c} BMAN_{cjk} - SMAN = 0 \tag{1.B.23}$$

Inventory of Manure Production, Application and Disposal:

$$SMAN + DMAN - TMAN = 0 \tag{1.B.24}$$

Nitrogen available per ton of Manure Produced:

$$NAV = (NMAN * 0.436) / TMAN \tag{1.B.25}$$

Phosphate available per ton of Manure Produced:

$$PAV = (PMAN * (0.692 / 0.44)) / TMAN \tag{1.B.26}$$

Starter Nitrogen for Crops:

$$\sum_{k}\sum_{j} sn_{jk}\left(CS_{jk} + CG_{jk}\right) + \sum_{k}\sum_{j} snca_{jk}\left(CSA_{jk} + CGA_{jk}\right)$$
$$+ \sum_{k}\sum_{j} snco_{jk}\left(CSO_{jk} + CGO_{jk}\right) + \sum_{k}\sum_{j} sno_{jk}\left(OG_{jk}\right) - BSNIT \le 0 \tag{1.B.27}$$

Nitrogen (less Starter N) for Crops ($C = 1, \ldots, 8$):

$$nc_{jk} C_{jk} - BNIT_{cjk} - (NAV * BMAN_{cjk}) \le 0 \tag{1.B.28}$$

Phosphorus for Crops ($C = 1, \ldots, 8$):

$$phc_{jk} C_{jk} - BPH_{cjk} - (PAV * BMAN_{cjk}) \le 0 \tag{1.B.29}$$

Potash for Crops:

$$\sum_{k}\sum_{j} potc_{j}\left(CS_{jk} + CG_{jk} + CSA_{jk} + CGA_{jk} + CSO_{jk} + CGO_{jk}\right) + \sum_{k}\sum_{j} pota_{j} A_{jk}$$
$$+ \sum_{k}\sum_{j} poto_{j} OG_{jk} - BPOT \le 0 \tag{1.B.30}$$

Rotation Soilk-CA: ($k = 1,2,3$)

$$4\sum_{j}\left(CSA_{jk} + CGA_{jk}\right) - \sum_{j} A_{jk} \le 0 \tag{1.B.31}$$

Rotation Soilk-CO: (k = 1,2,3)

$$4\sum_{j}\left(CSO_{jk} + CGO_{jk}\right) - \sum_{j} OG_{jk} \le 0 \tag{1.B.32}$$

Rotation Soilk-C: (k = 1,2,3)

$$3\sum_{j}\left(CSA_{jk} + CGA_{jk} + CSO_{jk} + CGO_{jk}\right) - \sum_{j}\left(CS_{jk} + CG_{jk}\right) = 0 \tag{1.B.33}$$

APPENDIX 1.C

ESTIMATING NITRATE RUNOFF AND LEACHING

The Nitrate Runoff and Leaching Model

Table A.1: Regression model to estimate N runoff and leaching on cornfields[1]

	Runoff		Leaching			
	All soils		A and B		C Soils	
Variable[2]	Estimate	Mean[3]	Estimate	Mean[3]	Estimate	Mean[3]
CON	-4.402		-75.568		-42.276	
NITRUN			-6.739	*NRO*	-11.576	*NRO*
SQNITRUN			2.119	*NRO*	3.880	*NRO*
HYDA	-0.453	0.159	0.290	0.199		
HYDB	-0.359	0.640				
LOGORG	3.241	1.466	5.235	1.472	0.876	1.439
SQLOGORG	-1.040	2.178				
LOGKAY	0.058	-1.216	-5.594	-1.233	-3.838	-1.149
LOGMINN	-0.581	4.271	5.442	4.260	-0.357	4.318
LOGPRECIP	0.652	*PPT*	5.768	*PPT*	7.593	*PPT*
LOGPRSTM	0.089	*PPT*				
SQLOGPRSTM	0.023	*PPT*	0.056	*PPT*	0.068	*PPT*
LOGFRSTM			0.256	*PPT*	0.098	*PPT*
SQLOGFRSTM	0.005	*PPT*	0.094	*PPT*	0.080	*PPT*
LOGLBMAN	0.628	*NLP*	4.824	*NLP*	3.916	*NLP*
LOGORGH1			-2.127	2.643	-1.259	3.017
LOGKAYH1			2.287	-2.221	2.062	-2.535
LOGH1			5.638	1.806	4.663	2.066
LOGSLP			-1.154	1.466	-0.525	1.660
LOGSLPH1			0.453	2.719	0.209	3.578
LAGCORN			-0.668	0.000	-1.167	0.000
LOGROT			-0.627	1.534	-0.417	1.347
NITPRSTM			0.363	*NRO*	0.280	*NRO*
LOGHRSTM			0.039	*PPT*	0.116	*PPT*
MANURE			0.235	*NLP*	0.102	*NLP*

[1] Modified from Boisvert, *et al*., 1997.
[2] Variables defined in section following on the Nitrate Runoff and Leaching Equations.
[3] The mean values for field application of nitrogen and manure, denoted *NLP,* come out of the non-linear programming model solutions; *NRO* are nitrate runoff estimates determined in the model following the Nitrate Runoff and Leaching Equations; *PPT* represents precipitation means for the sample of rainfall data. All other means are from Boisvert, *et al*., 1997.

The Nitrate Runoff and Leaching Equations

Variable and Symbol Definitions:

CON = Constant;

EXP = Exponential;

$FRSTM_{.Y}$ = Rainfall in storms w/in 14d of fertilizer application in year *y* (*y* = 1,…,30) (in.);

H1 = Soil horizon depth (in.);

$HRSTM_{.Y}$ = Rainfall in storms w/in 14d of harvest in year *y* (*y* = 1,…,30) (in.);

$HYD_{.X}$ = Dummy for hydrologic soil group *x* (*x* = A, B, C);

KAY = K erodibility factor;

LAGCORN = Dummy of corn in previous year;

$LBMAN_{.Z}$ = Total N application on crop land *z*[16] from manure and commercial fertilizer (z = 1,…,Z) (lbs.);

$LCH_{.X.Y.Z}$ = Estimation of leaching for soils of hydrologic group *x* in year *y,* for corn cropping activity *z* (*x* = A, B and C; y = 1,…,30; and z = 1,…,Z) (lbs.);

$LCoef_{V}$ = Coefficient for variable *v* from regression function for leaching (*v* = 1,…,V);

LMn_{V} = Mean value for variable *v* from regression function for leaching (*v* = 1,…,V);

LOG = the (natural) Logarithm;

$MANURE_{.Z}$ = Dummy for manure application on corn crop land *z* (*z* = 1,…,Z);

MINN = N mineralized by soil (lbs./acre);

$NITLCH_{.X.Y.Z}$ = Logarithm of estimated N leaching for soils of hydrologic group *x* in year *y,* for corn land *z* (*x* = A, B and C; y = 1,…,30; and *z* = 1,…, Z) (lbs.);

$NITRUN_{.X.Y.Z}$ = Logarithm of estimated N runoff for soils of hydrologic group *x* in year *y,* for cropping activity *z* (*x* = A, B and C; y = 1,…,30; and *z* = 1,…,Z) (lbs.);

ORG = Organic matter content (percent);

$PRECIP_{.Y}$ = Total annual rainfall in year *y* (*y* = 1,…,30) (in.);

$PRSTRM_{.Y}$ = Rainfall in storms w/in 14d of planting in year *y* (*y* = 1,…,30) (in.);

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[16] *z* is land classification for cropping activity *c* on land class *k* and soil P-level type *j* (*c, j* and *k* are as defined for the NLP model in Appendix B).

$RCoef_V$ = Coefficient for variable *v* from regression function for runoff (*v* = 1,…,V);

RMn_V = Mean value for variable *v* from regression function for runoff (*v* = 1,…,V);

ROT = Years of corn in 10 year rotation;

$RUN_{.X.Y.Z}$ = Estimation of runoff for soils of hydrologic group *x* in year *y,* for corn cropping activity *z* (*x* = A, B and C; y = 1,…,30; and *z* = 1,…,Z) (lbs.);

SLP = Average field slope (percent);

SQ = Squared;

$TLCH_{.Y.Z}$ = Estimation of leaching for soils in year *y* and for cropping activity *z* (*z* = 1,…,Z) (lbs.);

$TRUN_{.Y.Z}$ = Estimation of runoff for soils in year *y* and for cropping activity *z* (*z* = 1,…,Z) (lbs.);

<u>Equations 1.C.1 – 1.C.7: Estimating Nitrate Runoff and Leaching</u>

Nitrogen loss in runoff:

$$\begin{aligned}NITRUN_{.X.Y.Z} &= RCoef_{CON}*RMn_{CON} + RCoef_{HYD.X}*RMn_{HYD.X}\\ &+ RCoef_{LOGORG}*RMn_{LOGORG} + RCoef_{SQ.LOGORG}*RMn_{SQ.LOGORG}\\ &+ RCoef_{LOGKAY}*RMn_{LOGKAY} + RCoef_{LOGMINN}*RMn_{LOGMINN}\\ &+ RCoef_{LOGPRECIP}*RMn_{LOGPRECIP.Y} + RCoef_{LOGPRSTM}*RMn_{LOGPRSTM.Y}\\ &+ RCoef_{SQ.LOGPRSTM}*RMn_{SQ.LOGPRSTM.Y} + RCoef_{SQ.LOGFRSTM}*RMn_{SQ.LOGFRSTM.Y}\\ &+ RCoef_{LOGLBMAN}*RMn_{LOGLBMAN.Z} \qquad (1.C.1)\end{aligned}$$

Square of nitrogen loss in runoff:

$$SQNITRUN_{X.Y.Z} = SQ(NITRUN_{.X.Y.Z}) \qquad (1.C.2)$$

Nitrogen loss in leaching:

$$\begin{aligned}NITLCH_{.X.Y.Z} &= LCoef_{CON}*LMn_{CON} + LCoef_{HYD.X}*LMn_{HYD.X}\\ &+ LCoef_{NITRUN}*NITRUN + LCoef_{SQ.NITRUN}*SQNITRUN\\ &+ LCoef_{LOGORGH1}*LMn_{LOGORGH1} + LCoef_{LOGORG}*LMn_{LOGORG}\\ &+ LCoef_{LOGKAY}*LMn_{LOGKAY} + LCoef_{LOGKAYH1}*LMn_{LOGKAYH1}\end{aligned}$$

$$+ LCoef_{LOGH1}*LCoef_{LOGH1} + LCoef_{LOGSLP}*LMn_{LOGSLP}$$
$$+ LCoef_{LOGSLPH1}*LMn_{LOGSLPH1} + LCoef_{LOGMINN}*LMn_{LOGMINN}$$
$$+ LCoef_{LAGCORN}*LMn_{LAGCORN} + LCoef_{LOGROT}*LMn_{LOGROT}$$
$$+ LCoef_{LOGPRECIP}*LMn_{LOGPRECIP.Y} + LCoef_{SQ.LOGPRSTM}*LMn_{SQ.LOGPRSTRM.Y}$$
$$+ LCoef_{NITPRSTRM}*LMn_{NITRUN.X*\ LOGPRSTRM.Y} + LCoef_{LOGFRSTM}*LMn_{LOGFRSTRM.Y}$$
$$+ LCoef_{SQ.LOGFRSTRM}*LMn_{SQ.LOGFRSTRM.Y} + LCoef_{LOGHRSTRM}*LMn_{LOGHRSTRM.Y}$$
$$+ (LCoef_{MANURE} / 20) *LMn_{MANURE.} + LCoef_{LOGLBMAN}*LMn_{LOGLBMAN.Z} \quad (1.C.3)$$

Exponential of runoff:

$$RUN_{.X.Y.Z} = \text{Exp}\ (NITRUN_{.X.Y.Z}) \quad (1.C.4)$$

Exponential of leaching:

$$LCH_{.X.Y.Z} = \text{Exp}\ (NITLCH_{.X.Y.Z}) \quad (1.C.5)$$

Total runoff from soils A, B and C:

$$TRUN_{.Y.Z}{}^{17} = 0.07*RUN_A + 0.31*RUN_B + 0.62*RUN_C \quad (1.C.6)$$

Total leaching from soils A, B and C:

$$TLCH_{.Y.Z} = 0.07*LCH_A + 0.31*LCH_B + 0.62*LCH_C \quad (1.C.7)$$

[17] Consistent with the weather, cropping and soils data used, we assume that the proportion of soils in each of the hydrologic groups follows the classification for the Western Plains Region in New York (the 1992 National Resource Inventory).

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CHAPTER 2

ASSESSMENT OF NEW YORK'S POLLUTION DISCHARGE ELIMINATION PERMITS FOR CAFOS II: REGIONAL ANALYSIS[1]

Summary

In this paper, we apply mathematical programming methods to account explicitly for restrictions on land application of nutrients and to analyze the effects on measured outcomes of farm management adjustments to the nutrient policy and to recent changes in relevant agricultural prices. In particular, using a set of unique data, we assess the effects of new regulations for nutrient management by confined animal feeding operations (CAFOs) on (1) farm income, (2) land use, (3) manure and fertilizer management and, (4) environmental quality for an important dairy production region in New York. Our mathematical methods also allow us to make distinctions between the value of land for production and as a manure disposal site so that we can assess the differential effects of the land nutrient application standards on the economic value of land.

The results indicate that dairy ration adjustments in response to the current high prices of traditional feed ingredients lead to increased nitrogen and phosphorus content in dairy waste. In addition, crop nutrient applications from manure far exceed the critical uptake levels for optimum yield and increase the risks of nutrient loading to the environment. We showed in a related paper using representative farm programming methods that while the CAFO regulations correct for the identified problem, the reductions in nutrient loading risks could be accompanied by significant losses to farm income[2]. Our current application to an important dairy production

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[1] Enahoro, D., T. M. Schmit and R. N. Boisvert. New York Pollution Discharge Elimination Permits for CAFOs, Management Adjustment and the Environment: Regional Analysis. In Preparation.
[2] See farm-level analysis of the implications of CAFO regulations in Chapter 1.

region in Western New York further buttresses this point. In addition, we demonstrate that farm net revenue is sensitive to the availability of nearby land suitable for manure disposal. Further, the new nutrient restrictions require that about half of the manure produced on the dairy farms in the region be transported off-site for disposal so that crops with higher potential for absorbing field nutrients are more attractive than would otherwise be the case. The shadow prices for CAFO land with low soil phosphorus rise, reflecting not only its value in crop production but also its value as a site for manure disposal. These values reflect what the CAFOs could pay for additional land, and this price falls as the distance to the CAFO increases.

Introduction and Research Objectives

Regulations on land nutrient application on confined animal feeding operations (CAFOs) in New York may exacerbate the pressure on livestock and dairy operating margins brought about by the global recession-driven lowered demand for livestock and dairy products and high feed ingredient prices. While feed prices fell in 2009 below the record-high prices of the previous year, they remained well above historic levels. To reduce the associated rising expenditures on animal feed, animal feeding operators have necessarily made adjustments to their farm and feed management.

Dairy producers, for example, have looked to growing, rather than purchasing their own feed and have explored the options for including less traditional feed ingredients such as distillers dried grains and solubles (DDGS) in their dairy feed rations. In Western New York, availability of DDGS and the possibilities of increased supplies from an expanding bio-fuels industry have made more attractive the prospects for using these low-cost alternatives as feed ration ingredients. Research however suggests that inclusion of the less conventional feed ingredients could increase the potential for nitrogen and phosphorus loading to the environment (Schmit, *et. al.*, 2009). The outlook for using the low-cost feed rations is thus dampened, particularly when considered in light of the recent inclination of environmental policy toward more stringent regulations on nutrient discharge to the environment by agriculture.

The increased attention on agricultural operations follows from increased risks to ground and surface water quality in the United States from growing numbers of animal feeding operations being concentrated in smaller areas.[3] In particular, federal and local policies for environmental quality have focused more attention on reducing the negative impacts of what are considered the most relevant of the animal feeding operations from an environmental pollution perspective, the CAFOs. As such, CAFO management decisions on food and grain production and on feed ration composition must be evaluated with considerations for their effects on the environment and in light of emerging regulations on land nutrient applications.

In research related to this paper, we used representative farm programming methods to analyze the implications for a New York dairy producer of new CAFO regulations on land application of nutrients, measuring the changes to farm income and environmental nutrient loading and investigating the prospects for including low-cost feed ingredients in rations.[4] Our results indicated that the representative dairy farm needed to transport 40 percent of manure produced on-farm to nearby land for disposal. This suggested important implications of the nutrient standards for regional environmental quality.

The current research continues that analysis by investigating the regional implications of the new land nutrient application policy. We use mathematical programming methods to account for the new restrictions on land application of nitrogen (N) and phosphorus (P). The new restrictions are based on comprehensive

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[3] See Gollehon, *et al*., 2001, for a detailed discussion of manure nutrient pollution by CAFOs.
[4] See Chapter 1.

nutrient management plans (CNMPs) that CAFOs must develop to obtain and maintain pollution discharge elimination permits for New York State that the farms need to operate. In this paper, we determine in association with the new nutrient standards: (1) changes in farm incomes, (2) changes in land use and (3) region-wide effects on environmental quality as measured by changes in phosphorus runoff. The new nutrient restrictions are specific to CAFOs so that it is entirely possible that manure exported off of CAFOs in response to the increased regulations end up on nearby farms that are not directly affected by the restrictions, increasing manure application on those lands, with regional implications. By mathematically distinguishing the value of land for production from its value as manure disposal site, we further assess (4) the differential effects of the land nutrient application standards on the economic value of land. Throughout, our analysis is focused on an important dairy production region in Western New York.

Our research is unique in several regards. By explicitly modeling the dairy operation from a whole-farm nutrient management perspective that is consistent with nutrient management restrictions set by the relevant Land Grant University (in this case Cornell University), it is one of the first attempts to assess the impact of new state-specific nutrient standards. In particular, we model the effects of CNMPs that (1) set manure and fertilizer application at rates consistent with realistic crop yield objectives, (2) limit nitrogen and phosphorus application where risk of runoff is high and (3) prohibit manure or P application where agronomic soil test phosphorus is excessive. Since the nutrient standards that we model are only proposed, and not yet in effect, our research provides information that is important for the further design, and eventual implementation of the policy.

Our analysis is made possible through the availability of two unique data sets developed for agricultural production regions in New York State: (1) the distribution of cropland on dairy farms according to crop productivity class and (2) multi-year summaries of soil nutrient tests. Using these data and results from previous research, we are also able to incorporate into our model empirical methods for estimating nutrient runoff and leaching that are calibrated specifically for New York State. We go on to estimate the effects of the regulations on the distributions of phosphorus and nitrogen residuals based on historical weather conditions and are able to interpret the results from a safety-first perspective; e.g., assessing the probabilities that these residuals will exceed certain critical thresholds with and without the regulations.

Using a set of non-linear constraints, we allow for the endogenous determination of the nutrient composition of manure from feeding combinations of animal rations. Adjustments to the dairy rations that are driven by price concerns where there are no nutrient regulations lead to increased nitrogen and phosphorus content in manure and to on-farm application of manure nutrients well in excess of the soil test levels beyond which no crop yield responses to additional nutrients are expected. From our earlier work using farm-level data we found that the regulations could correct for this “excess nutrient’ problem, albeit with potential significant reductions in net farm income[5]. In particular, reduced opportunities for manure application could increase the costs of off-farm manure disposal.

We account for the cost implications of transporting manure to off-farm recipients in detail in this extension of the analysis to the dairy producing region. As off-farm manure disposal costs increase, available farmland can take on added value as a manure disposal site. In particular, unregulated land that can receive additional manure increases in economic value relative to CAFO farmland on which nutrient application is restricted. By applying a mathematical treatment of the Kuhn-Tucker first-order necessary conditions derived from our optimization model to a stylized case

[5] See Chapter 1.

of the CAFO adjustments and rising costs of off-farm manure disposal, we show how the economic value of land changes in response to the land nutrient application policy.

What follows, we outline the new nutrient restrictions guiding CAFOs in New York State, and first summarize relevant characteristics of the New York dairy producing region that is the focus of our analysis. Next, we discuss the basic mathematical framework of our model and its empirical application and describe the data. We then show how to extend the base model to include the new nutrient application standards; to account for changes in the costs of off-site manure disposal; and to measure empirically the phosphorus and nitrate loadings associated with the dairy management adjustments. The results of the empirical analysis are then presented and discussed. We compare solutions to the programming model for a base case with no nutrient standards and a policy scenario in which we simulate the new nutrient regulations. Finally, we discuss the implications of our findings and offer conclusions that can be drawn from this study.

Land Nutrient Management and CAFO Regulations in New York

In general, i.e., from an agronomic standpoint, crop producers may be concerned with supplying enough nutrients to meet current crop requirements for optimal yield and to raise soil test levels to reduce (future) fertilizer needs. As the soil test levels increase however, the risks of exceeding environmental thresholds could increase. Environmental thresholds are defined as those levels at which nutrients in soils exceed the capacity of the soils for retention and thus increase the potential for nutrient loss to ground and surface waters.[6] A goal of environmental policy related to ground and surface water quality is to limit fertilizer and manure applications that increase the risks of soil nutrient runoff and leaching. In New York, as in much of the

[6] See Ketterings, *et. al.*, 2005.

United States, phosphorus runoff has been identified as an important nutrient loading risk and animal feeding operations are important contributors to the runoff.

For example, a state-wide multi-year soil survey showed that following a steady rise in soil test P levels since the 1980s, up to 47 percent of all soil samples in 2001 were at or above the critical agronomic soil test P for field crops (Ketterings, *et. al*., 2005). In particular, high levels of soil P were found for samples from the dairy producing regions in Western New York.[7] With increasing concentrations of animal feeding operations in the high dairy producing regions, the federal regulations on land nutrient applications and their adaptation in states like New York have been changing to more directly address the growing threats of phosphorus losses from agricultural field runoff and leaching (see USDA-EPA, 1999 and USDA-NRCS 2003a, for example).[8] The nutrient management guidelines for New York are developed by Cornell University, the Land Grant University for the state.

The guidelines on nutrient application on New York CAFOs take into consideration the results of soil testing for samples from agricultural lands across the state and restrict the application of soil nutrients (particularly N and P) accordingly. The CAFOs are required to obtain state pollution discharge elimination system (SPDES) permits in order to operate, and one of the conditions for maintaining the permit is that the CAFOs develop and implement CNMPs (NYSDEC, 2003). The CNMPs in turn are guided by the Natural Resources Conservation Service (NRCS) Code 590 standard that emphasizes the reduction of nutrient losses to ground and surface water from the over-application of fertilizer and manure and the prevention of direct manure losses to streams and lakes (USDA-NRCS, 1999). To standardize the

[7] Ketterings, *et. al*., 2005 reported the highest soil test P levels in the vegetable production regions in Long Island and in the vegetable, fruit and dairy producing regions in Western New York.
[8] A 2001 proposal for revision of the Clean Water Act of 1998 increased the number of animal feeding operations regulated under the Act, and further recommended that CAFOs with insufficient land be required to export excess manure to off-site recipients.

assessment of P loss risks from agricultural fields with different sources of nutrient loss and runoff and leaching transport factors, many states have developed and/or adopted the use of phosphorus and nitrogen loss indexes that are used in conjunction with soil test values for field nutrient planning and application policy purposes.

In New York, the phosphorus runoff index (PI) and the nitrogen leaching index (NLI) are useful in developing the nutrient management guidelines for CAFOs (see Ketterings, *et al*., 2003a and 2003b). On fields where P loss is considered the larger nutrient loading threat, a P-based management strategy is followed, and the PI is the relevant index. The NLI is the important index for N-based nutrient management. We summarize the application of PI and NLI to nutrient management planning in New York in Appendix 1 (see Chapter 1). A nitrogen-based management strategy applies manure and commercial fertilizers at rates that supply all of the nitrogen recommendation for a crop and account for volatilization losses. Typically, this application regime results in the over application of phosphorus. P-based nutrient management, on the other hand, tends to make the application of nitrogen fertilizers necessary (USDA-NRCS. 1999).

Our modeling of the nutrient restrictions on N and P for field crops on CAFOs in New York follows the Cornell University guidelines (as in Ketterings, *et al*., 2003a and 2003b). Crop nutrient applications are limited to the agronomic uptake levels and soil P tests are used as indicators of P loss so that manure and fertilizer P application are further restricted on soils with medium to high soil test P. Further, we account for nutrient management specific to alfalfa cropping following Ketterings, *et al*., 2006. The relevant nutrient management conditions and allowable application rates are summarized in Figure 1.1 (see Chapter 1).

Phosphorus-based management is followed on corn and alfalfa land with soil (Morgan P) test of 40 lbs/acre and more. These soils are designated as the *high* soil test P (STP) class. P-based management is similarly followed on a *medium* (i.e. 9 – 39 lbs/acre of Morgan P) STP land class. While no manure or P fertilizers can be applied on *high* P soils, phosphorus may be applied on fields with *medium* STP land and is restricted to a proportion of the crop P-removal rates. A third class of land is designated the *low* STP with Morgan P values of less than 9 lbs/acre. This land class has the least restrictive nutrient application regime where manure and fertilizer applications can meet the entire crop P requirement. When the phosphorus management-imposed conditions for manure and fertilizer application are met, a nitrogen condition is applied that accounts for the crop differential nitrogen requirements and utilization. For acres on which corn is grown, N application should not exceed the crop requirement levels necessary for optimum productivity.

Alfalfa cropping, on the other hand, can allow for a little more flexibility. Alfalfa may not require any manure application as it typically meets its nitrogen requirements through N fixation. However, alfalfa has the ability to reduce its N fixation activity when other sources of N are readily available so that it can better serve as a manure receiving site than corn (see Ketterings, *et al*, 2006). Manure P application can thus be allowed on alfalfa on the *low* and *medium* P soils that meet the crop phosphorus and nitrogen requirements net of nitrogen fixation. Sustainable nutrient management however would not allow for manure spreading on alfalfa grown on *high* STP soils.

We apply relevant soil test results for a three-county dairy producing region in New York to mathematical programming models that account explicitly for manure and fertilizer nitrogen and phosphorus restrictions on CAFOs. The model is solved for both a base case in which no nutrient standards are imposed and a policy case that simulates the nutrient standards following land nutrient application guidelines from Cornell. The effect of the policy is evident through a comparison of the results.

Selected Three-County Dairy Producing Study Region in New York

Our study region includes Genesee, Wyoming and Livingston counties. These three counties jointly host a little more than a quarter of all dairy farms with 500 or more milk cows in New York (USDA, 2009); and the counties constitute a significant portion of the Genesee River Watershed.[9] With their high concentration of dairy farms and geographical proximity and the natural barrier to off-site manure transportation created by the Finger Lakes bordering to the east of the region, these three counties are ideal for studying the regional implications of manure and fertilizer nutrient application restrictions on CAFO land, particularly when accounting for the transportation of excess manure to off-farm recipients. In Table 2.1, we summarize descriptive data of the three-county study region available from the USDA.

Table 2.1: Selected 2007 data for the three-county study region in New York[1]

	Genesee	Livingston	Wyoming	3CR[2] Total	3CR Mean[3]
Dairy Cows (no.)	21,449	20,408	38,497	80,354	40,177
Cropland on CAFOs (ac.)	41,889	39,402	76,202	157,493	78,746
Other Cropland[4] (ac.)	90,444	107,351	66,240	264,035	132,018
Dairy CAFOs (no.)	26	24	61	111	56
Cows/CAFO (no.)	825	850	631	-	724
Cropland/CAFO (ac./farm)	1,611	1,642	1,249	-	1,419
Other/CAFO[4] (ac./farm)	3,479	4,473	1,086	-	2,379
CAFOland/Cow (ac./cow)	1.95	1.93	1.98	-	1.96
Otherland/Cow[4] (ac./cow)	4.22	5.26	1.72	-	3.29

[1] Source: USDA. 2007 Census of Agriculture.
[2] 3CR is the three-county region.
[3] Region means are weighted averages for the three counties.
[4] Regional cropland that is not controlled by CAFOs. Location is unknown.

[9] The Genesee River, with its source in Pennsylvania, runs about 157 miles northward mostly through New York, from where it drains into Lake Ontario.

Wyoming County has the highest number of large animal feeding operations of the three counties, with 27 farms having 500 or more dairy cows and 61 farms with 200 and more dairy cows.[10] Livingston County with the smallest number of large dairy establishments has the highest number of dairy cows per farm. The average farm size for CAFOs in the three-county region is 724 dairy cows per farm, excluding dry cows and replacement heifers.

On average, more cropland is controlled per CAFO in Livingston or Genesee than in Wyoming County, and the estimated number of harvested acres rented or owned in the three-county region is 1,419 acres per CAFO. Cropland not controlled by the CAFOs in the region is estimated to be about 2,379 acres for each CAFO, or almost 70 percent more than what is available on the CAFO land. At first glance, this may suggest that the large animal feeding facilities have sufficient land available for off-site manure disposal when field nutrient restrictions prevent them from applying all of the manure that their operations produce on land that they directly control. However, regional crop land not controlled by the CAFOs is not necessarily available for use as manure receiving sites. Location, ease of access, spatial fragmentation of crop land and the willingness of crop producers or farmland owners to apply manure on their land are only a few factors that could determine availability of non-CAFO land for manure imports.[11] To analyze the regional implications of the new nutrient standards, we apply mathematical programming methods to data for the selected three-county region in Western New York.

[10] By NRCS definition, CAFOs with fewer than 300 dairy cows are small; 300 to 999 are medium and 1,000 or more are large for regulatory purposes. Small and medium CAFOs are regulated on a case-by-case basis. However, survey data on farm sizes available from the USDA do not follow this categorization. To avoid throwing out useful observations, we include all farms with more than 200 dairy cows in the USDA data in our definition of regulated CAFOs.

[11] Kaplan, *et al*., 2004 made alternative assumptions about the willingness of crop producers to accept manure as fertilizer substitutes in their analysis of economic and environmental implications of land nutrient application constraints.

Analytical Framework and Empirical Setting

Mathematical programming techniques have been applied to farm planning problems since at least the 1950's with the earlier applications relying almost exclusively on linear programming methods (e.g., Waugh 1951, Heady and Candler, 1958). More recent advances in theory and computational methods have allowed for mathematical programming models to relax the assumption of fixed input and output prices, accommodate management decisions and model management response to price and production risks in farm planning, amongst others (e.g., McCarl and Spreen 1980; Wui and Engle 2004; Boisvert and McCarl 1990). Programming methods have also been used extensively to evaluate new opportunities and challenges facing farm operators, including management responses to environmental policy (e.g. Casler and Jacobs 1975; Schmit and Knoblauch 1995). Recent studies have used mathematical programming techniques for the assessment of the implications of alternative soil nutrient application standards for manure nutrient management; to account for new nutrient management costs associated with environmental regulations compliance in the formulation of livestock feed; and to analyze the economic and environmental implications of federal regulations on land nutrient application (Feinerman, *et al*., 2004; Hadrich, *et al*., 2008; Kaplan, *et al*., 2004).

Using a regional optimization model, Kaplan, *et al*. (2004) provided important insights into the linkages between land nutrient restrictions and the local economy and environment. A constrained partial equilibrium model was used to illustrate the effects on sectors of the economy of imposing nutrient standards on the largest of AFOs. Results from that study showed a pass-through to local consumers of the costs of meeting the land nutrient standards in the form of higher prices. By adopting a nation-wide approach that considered U.S. farm production regions following USDA classification, the study by Kaplan, *et al*. (2004) accounted for regional differentiation in the policy effects due to differences in CAFO concentration (and manure production) and land availability. The regions in the study were of relatively large geographic scope, covering 2 to 11 states each.

In comparison to Kaplan, *et al*. (2004), Feinerman, *et al*., (2004) and Hadrich, *et al*., (2008) applied mathematical programming models to account for nutrient standards within the contexts of individual states. Feinerman, *et al*., (2004) used a mathematical programming model to determine the response of manure demand to nutrient standards in Virginia then incorporated the identified manure demand relationships into a highly stylized spatial equilibrium model to estimate the welfare costs of alternative soil N and P application standards on manure application. The Feinerman, *et al*., (2004) study assumed that crop farmers who do not own livestock or poultry can choose to use manure (produced by the animal feeding operations) or commercial fertilizers to meet their crop nutrient needs. The demand for manure by the crop farms was assumed to be relatively elastic and to depend on the relative prices of manure and commercial fertilizers; relative costs of spreading manure and fertilizers; manure nutrient concentration; and environmental regulations regarding the rates and methods of nutrient applications. Manure prices in turn were composed of the purchase prices at the supplier's gate and the costs of transportation to the recipient fields.[12] The model further took into account three strategies for manure and fertilizer application; two sources of farm manure; three possible scenarios for nutrient regulations; and a cropland availability constraint that imposed barriers to manure application in the short-term. However, the focus of the study on the short run where manure supply is completely inelastic led to the specification of an optimization model

[12] Manure suppliers could be regulated CAFOs with insufficient land to spread manure and farm gate manure prices include costs for storage and testing.

that did not include possibilities for production changes that could influence longer-term manure production and supply.

Hadrich, *et al*. (2008), on the other hand, allowed for variations in livestock production in their development of a representative farm model in Michigan. By incorporating manure management costs associated with environmental regulations in Michigan into the linear programming formulation of livestock feed rations, they demonstrated the possibility of formulating confined animal feed rations to jointly minimize feed and net nutrient disposal costs. This approach could account for costs of compliance with environmental regulations that may have been previously ignored.

In contrast to the cited studies, our current application of mathematical programming techniques to the assessment of soil nutrient regulations is state-specific, takes on a whole-farm management approach that allows for changes in animal and crop production and accounts explicitly for nutrient standards and nutrient management considerations in the farm manager's decisions on crop production as well as on feeding and other aspects of animal production. We impose NRCS nutrient application standards following Ketterings, *et al*., 2003a and 2003b. Our specification of the model for a base and a nutrient policy scenario allows us to isolate the effects of the nutrient regulations. We are able to include components in the model that link bio-energy feed ingredients, feed prices and manure nutrient loadings by using the CPM-Dairy program.[13] We accommodate the possibility for the dairy operation to use lower-cost feed alternatives as in Schmit, et al., (2009) so that we can assess the whole-farm nutrient management and planning response given DDGS in feed rations.

Using techniques developed by Vadas, *et al*. (2009) and to extend our now *non-linear* programming model, we determine phosphorus loss in runoff to the

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[13] The CPM-Dairy program software program for formulating and evaluating dairy feed rations was jointly developed by Cornell University, the University of Pennsylvania Veterinary College and the Miner Institute.

environment that is associated with crop fertilization. We use techniques developed in Boisvert, *et al*. (1997) to determine nutrient management-related nitrate runoff and leaching. The nutrient loss estimation techniques that we adopt were developed using markedly different strategies. Boisvert *et al*. (1997) derived equations for estimating N loading. These equations were estimated from simulated N runoff and leaching data. The data were generated for many common New York soils, a variety of weather conditions and management strategies using the Ground Water Loading Effects of Agricultural Management Systems (GLEAMS). On the other hand, Vadas *et al*., (2009) developed their methods for estimating P loss in runoff from extensive field studies and for a variety of soil, fertilizer management and climate conditions. The techniques in Vadas *et al*., (2009) are designed to be compatible with ground water transport models such as the Erosion-Productivity Impact Calculator (EPIC).

Further, using the Kuhn-Tucker conditions for optimality, we analytically determine the differential implications on economic value of land of the new restrictions on land nutrient applications and increases in the costs of off-farm manure disposal.

The Base Model

To assess changes in farm income, nutrient management, land use and land value, and environmental quality associated with the combined effects of new nutrient standards and changing feed prices for our three-county dairy producing region, we develop a base (no policy) mathematical programming model. The model represents the aggregate agricultural production of all the CAFOs in the study region. This modeling strategy is similar to the strategy in Kaplan *et al*. (2004), and the much earlier work (e.g., Heady and Srivastava, 1975), in which models are constructed for agriculture within USDA or other production regions. However, unlike many of these other models designed to study interregional agricultural adjustments to changes in national policy, ours is a model concerned with production adjustments on CAFOs within the region in response to CAFO nutrient management regulations.

The structure of the model is similar to the model in Schmit (1994) and Schmit, *et al*. (2009), and the formulation of the non-linear model is presented in Appendix 1.B (Chapter 1), along with the objective function and the 33 distinct sets of constraints. In contrast to that model, however, the one in this paper is designed to maximize expected annual revenues over expected variable costs of the CAFO's within the study region. A second distinguishing feature of the model is that the constraints for cow numbers, cropland and labor reflect estimates of the totals of these various resources currently controlled by the CAFOs in the study region. In so doing, we are assured that the production adjustments in response to nutrient policy remain consistent with the regional availability of important agricultural resources.

Input and output coefficients of the model reflect important production, cost and revenue relationships for the dairy CAFO operations. Key features of the model are a livestock component that determines production as well as feeding activities and a cropping component that assigns acres to various crops, accounts for restrictions on crop rotations, and categorizes available cropland by yield capability and agronomic soil tests. The soil test classifications have implications for the new nutrient restrictions that we discuss below. The livestock and cropping components of the model are interrelated in that crops grown on farmland owned or rented by the dairy operation can be fed to animals produced on the farm. Further, the animal and crop production activities are linked through nutrient management; e.g., levels of nutrients produced in manure are affected by the choice of feed rations and manure produced by farm animals can in turn supply nutrients to farm-grown crops. The model differentiates between the production of agricultural commodities and their uses.[14] Separate activities are also defined for the purchase of all feed ingredients and for major inputs such as labor, fuel and fertilizers.

Realistic assumptions are made about the available livestock, land and labor resources. The dairy CAFOs in the selected three-county region have about 80,354 dairy cows and control 157,490 acres (37 percent) of the harvested cropland in the region (see Table 2.1). Up to 1,607,080 hours of on-farm labor are estimated to be available annually and additional off-farm labor can be obtained at two different wage levels. Equations 1.B.8 – 1.B.10 (Appendix 1.B, Chapter 1) sum up the three types of labor. Farm labor is used in livestock production and feeding activities as well as in crop production, including fertilizer and manure land application.

The dairy establishment in our model summarizes the makeup for a typical regulated CAFO in the dairy producing region; assuming characteristics similar to those of equivalently-sized farms participating in the Cornell Dairy Farm Business Summary program (see Knoublauch, *et al*., 2008).

Livestock Production and Feed Rations

The dairy cows in the model are assumed to weigh 1,400 pounds and to produce 21,000 pounds of milk per cow per year on average. Milk cows, dry cows and replacement heifers are raised on rations formulated from purchased and farm-grown feed. While the model is regional in focus, one can conveniently and without loss of generality discuss the structure of the model by using an "average" farm constructed by dividing the regional resource constraints by the number of CAFOs. For this "average" CAFO, the maximum herd size is restricted to 724 lactating cows

[14] For example, sale activities are clearly defined for milk, cull cows and cull calves, as are activities for the purchase of crops, and the growing and sale of farm-grown crops.

and the numbers of dry cows, heifers, cull cows and cull calves are constrained to be in appropriate fixed proportions to the number of milking cows (see Equations 1.B.2 – 1.B.5).

We use the CPM-Dairy program to generate alternative dairy rations for animal feeding that include the possibilities of feeding DDGS in the total mixed ration (TMR). The structure of the model allows us to demonstrate how the composition and amounts of final feed rations are affected by relative prices of the component feed ingredients. Ten (10) separate dairy cow activities are included in the model that differ in terms of the corn or hay-silage base and whether or not DDGS is included as feed ingredient. Where DDGS is included, the ration may contain either 10 or 20 percent DDGS on a dry matter basis, and a fat content of either 8 or 12 percent. The dairy cow activities are summarized in Table 1.1 (Chapter 1).

Separate activities are included for feeding dry cows and raising heifers, although these activities allow for more limited feeding options than for the lactating cows (shown in Table 1.2, Chapter 1). Further, milk production is not allowed to fall relative to the no-DDGS rations, for any of the feeding activities that include the bio-energy byproducts. The constraint on milk production limits the potential for significant increases in P content of the feed rations and manure that could otherwise accompany increased availability of DDGS (e.g., Hadrich, *et al*., 2008). There is considerable empirical support for this constraint on the results of the CPM-Dairy program (e.g., Schmit, *et al*., 2009).

Crop Production and Cropland Classifications

Alfalfa hay, orchard grass, corn silage and corn for grain can be purchased or grown. Crops grown on the farm follow cropping rotations typical of the region. Harvested crops are fed to the animals or sold, although corn silage can be grown for on-farm feed but not sold. Equations 1.B.12 – 1.B.15 define the constraints on growing, buying and selling of crops and on their use as feed. Restrictions imposed on the crop rotations are specified in Equations 1.B.31 –1.B.33. The crop rotations influence field crop requirements for nutrients (see Table 1.3). Field crop requirements in turn are important for manure management, particularly for the simulation of the nutrient policy scenario that we outline later in our discussion.

The average CAFO owns or rents 1,419 acres of cropland. Land that is so controlled by the CAFO is assigned to three classes based on the soil characteristics and corn silage yield potential; i.e., low, medium and high soil capability class, or 4.9, 5.3 and 5.9 tons of dry matter per acre, respectively. Twenty three percent of the land is assumed to be of the lowest quality; medium quality land account for 66 percent of the cropland and 11 percent of the land is assumed to be of high quality. Available land is also distinguished by soil test phosphorus (STP) status; i.e., agronomic soil testing (Morgan) phosphorus levels before manure and fertilizer applications for the current cropping season. The soil phosphorus classifications give an indication of residual P build-up from previous years. Table 2.2 presents the crop yield capability and soil phosphorus level classifications of the regional CAFO land. Sixty percent of CAFO cropland is in the medium or high STP category.[15] The soil-crop nutrient requirements have implications for manure and fertilizer applications on the land.

Field Phosphorus and Nitrogen Management

Except for starter nitrogen that must come from commercial fertilizer, crop N and P requirements on the farm can be met using either of manure or fertilizer. Fulfillment of crops' starter N needs is represented by Equation 1.B.27.

[15] The proportions of soils in the crop productivity classifications are based on soil survey data as explained in Boisvert *et al.*, 1997. Soil P test distribution follows Rao *et al.*, 2007. The soil P test distributions are assumed constant across the soil productivity classes.

Table 2.2: Distribution of land on the CAFOs

	Mean[1] (Range)	% of Land in Class
Land (acres)	1,419	100
Productivity (tons of corn grain/ac)[2]		
Land Class 1	113	23
Land Class 2	121	66
Land Class 3	135	11
Soil Test P (lbs/ac)[3]		
Low	4 (0 – 8)	40
Medium	24 (9 – 39)	53
High	120 (40 – 200)	7
Hydrologic Groups		
Hydrologic Group A	-	7
Hydrologic Group B	-	31
Hydrologic Group C	-	62

[1] Mean values for CAFOs in the selected three-county dairy production regions. Land values from USDA, 2009. Other means are obtained from:
[2] Boisvert, *et al*., 1997.
[3] Rao, *et al*., 2007.

Our model endogenizes the rates of manure application, matching the amounts of manure nutrients available for crop use with the nutrient requirements of the crops.[16] Crop requirements not met by manure nutrients can be purchased as fertilizers. To match crop requirements with nutrient availability in manure, we accumulate the total volume of manure produced from lactating and dry cows and heifers on the average CAFO as in Equation 1.B. 20. The amounts of N and P nutrients produced in the manure are similarly accumulated (Equations 1.B.21 – 1.B.22). Manure that is produced on the farm is spread on crop acres or transported to off-farm locations. Equation 1.B.23 takes inventory of manure production, application,

[16] In Schmit (1994) and Schmit et al. (2009), average nutrient levels were assumed and manure was applied to the fields at predetermined rates of 10 or 20 tons per acre.

and transportation to off-farm recipients. Not all of the manure nutrients produced on the farm are available for plant uptake and we account for handling, storage and field losses in Equations 1.B.25 and 1.B.26. We also account for field differences in the soil-crop nutrient needs. Manure nutrient application is such that it could just meet, or exceed the nutrient requirements (see Equations 1.B.28 and 1.B.29).

We model land application of manure and commercial fertilizers under two conditions. The first case that we have discussed so far assumes no restrictions on the land application of nutrients so that the dairy operation can spread up to 100 percent of the manure that is produced on the cropland. Under the alternative simulations, farm nutrient planning follows NRCS guidelines for nutrient application to field crops.

Simulation of the New Nutrient Restrictions

We assume in the regional dairy model that phosphorus-based nutrient management is followed on crop fields for which manure or fertilizer P applications imply significant environmental P loading risks. Nitrogen-based management is adopted otherwise. STP levels determine the levels of P runoff risks. By assuming similarity in important soil characteristics such as the field topography and soil depth, we further assume that the differences in potential for P loss to surrounding waters are due entirely to differences in how manure and fertilizer nutrients are managed on the land classes. We restrict nutrient applications based on the soil P levels of the cropped land as shown in Figure 1.1 (Chapter 1). To do this, we adopt relevant means and distributions for the STP land classes using soil survey data of field phosphorus levels available for our dairy producing region (Rao, *et al.*, 2007).

Following the survey data, we model 8 percent of the land as high STP so that no further P application is allowed on the land. Commercial N fertilizers may be used to fulfill N requirements on these fields, up to the agronomic N crop-uptake level.

Also, 48 percent of the land is of the medium STP category and allows for only 40 percent of the crop P requirement to be met from manure and commercial fertilizers. The rest of the land has low STP and can receive soil amendments up to its entire P needs. In general, soils with medium or low STP receive manure at the application rates at which either of P or N requirements of the crop is fulfilled, whichever is more limiting. The nutrient requirement beyond that supplied by manure at this rate is then fulfilled using N or P commercial fertilizers, whichever is needed. We apply the relevant STP land classifications and nutrient application conditions to the entire cropland acres available to the CAFOs in the region, assuming that land quality for the three STP land classes follow the distributions reported in Table 2.2.

The nutrient policy limits the over-application of manure nutrients so that there is an increased need for CAFOs to transport manure to off-site locations. We thus extend the regional model to include alternative manure disposal costs. Further, we establish analytically the implications of off-site disposal for the shadow value of farmland, and these can differ by soil productivity and STP class. We do this through a manipulation of the (Kuhn-Tucker) first- order necessary conditions obtained from solving the objective and constraint equations for a model optimum.[17] As part of the analytical results, we show how the economic value of land could respond to the nutrient policy and to increased costs of off-farm manure disposal. For example, in the base case where no nutrient regulation is in effect, nutrient management may not account for soil inherent nutrients and over-application of nutrients results. Land values in this case are uniform for all of the soil test land classes given the crop yield capability of soils. However, implementation of the new nutrient restrictions forces the dairy management to recognize and account for nutrients (e.g., phosphorus) already in

[17] The analytical results are reported in Appendix 2. While the results are established for a rather stylized version of the model, the analytical results do generalize to the full model.

the soil so that land with high soil nutrient (P) content has higher value. Thus, less fertilizer (P) needs to be purchased or applied. The new nutrient policy also requires that manure produced in excess of what the farm requires for nutrient needs be exported to manure receiving locations. The economic value of land would thus be higher on the high STP land class (than on medium and low STP land) and this holds for as long as the dairy management can ship excess manure off the farm at no additional costs. It also holds for off-farm manure disposal costs that are low enough they do not off-set the added value to high P land from recognizing the value of P already in the soil. As manure disposal costs rise, however, the dairy management seeks to ship less manure off the farm to maintain farm incomes. One way to do this is to spread more of the manure produced by farm animals on farmland controlled by the CAFOs. Consequently, farmland on which more manure can be spread becomes increasingly important and valuable. Eventually the value of lower STP soils to the dairy operations rises above that of soils with higher levels of P available for crop uptake. We observe this as a switch in the (magnitude) order of the shadow prices for high versus low (medium) STP land.

Off-Site Manure Disposal Costs

Manure produced on the farm and not applied to the fields as crop nutrients is disposed of off-site (see Equation 1.B. 23). We impose manure disposal costs to assess the implications for the new nutrient restrictions and for dairy CAFOs in the region due to restrictions in land manure application. The off-site manure disposal costs implicitly represent the distances that dairy operations must travel to find suitable land for manure disposal (see Hadrich, *et. al*, 2008 and Harrigan, 2001). These distances could increase substantially for CAFOs in regions with high concentrations of similar operations. The net manure disposal cost in our model can account for the distances traveled by CAFOs to spread manure on unregulated land, and is a mark-up on the unit cost of spreading manure on fields and the commercial value of the nutrients in the manure. The net manure disposal cost per ton is represented mathematically in Equation (2.1):

$$TC = C_{DM} + C_{MS} - V_{MP} - V_{MN} \qquad (2.1)$$

where TC is the net cost per ton of manure disposed. C_{DM} is the unit transport cost and is a function the distance covered.[18] C_{MS} is the unit cost of spreading manure on the field. V_{MP} and V_{MN} are the values of phosphorus and nitrogen in a ton of manure, respectively, and are (all other things being equal) equivalent to the market price of fertilizer P and N.[19] Regulated dairy operations are assumed to bear the direct costs of shipping excess manure to off-site locations (i.e., C_{DM}). It is also reasonable to assume that the CAFOs spread the manure on the receiving farmland and incur additional costs (C_{MS}).[20]

Further, since manure nutrients are shipped off the farm in our model only in response to the new nutrient restrictions prohibiting excess nutrient applications on the land, we appropriately assume that nutrients in exported manure are of no direct value to the regulated CAFOs. As such, V_{MP} and V_{MN} can assume zero value in which case TC, the net cost to the CAFOs per unit of manure disposed, is strictly positive. However, the value of the nutrients in the (CAFOs') shipped-off manure may be

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[18] The determinants of C_{DM} could include the volume of manure shipped off-farm and the technology used to ship the manure (e.g. Harrigan, 2001). The exact relationship is not shown here.

[19] Manure nutrients in our model are considered substitutes for fertilizers and do not take on (lose) additional value over fertilizer market prices. However, P and N occur together so that manure P (N) may be needed by crops but can not be used due to the nutrient restrictions binding on N (P). In this case P (N) in manure could take on a value less than the market price for P (N) fertilizer.

[20] From an efficiency perspective, it is unlikely that CAFOs would off-load manure on receiving farms to have them re-load the manure onto other spreaders for field application.

evident for “importing” crop farms such that the CAFOs can receive payment for the manure. In this case, the dairy operators may negotiate to spread manure on disposal sites in return for some payment for the manure nutrients. Positive values for V_{MP} and V_{MN} then offset all or part of C_{MS}, the costs of spreading manure on the land. There is a dampening effect on the overall cost of off-farm manure disposal. In our model, we assume a single value for the unit cost of off-site manure disposal that encompasses manure volumes, distances covered to find suitable land, expenditures for spreading manure on receiving land not controlled by CAFOs, and possible payments received by the CAFOs for N and P in manure exports (as in Equation (2.1)). Our abstraction from the complexities is without loss of generality. We are still able to isolate the effects of a cost constraint to regulated animal feeding operations in high dairy producing regions of transporting excess manure to off-site fields to which manure nutrients can be applied given the new regulations. We investigate the implications for the CAFOs of the nutrient standards by setting the aggregated off-site manure disposal cost at a reasonably low value. By parametrically increasing this value, it is possible to observe the critical points at which current farm operations must change with rising manure disposal costs for the farm operations to remain optimal.

The dairy management adjustments to the new nutrient restrictions and to cost constraints on manure disposal also have important effects on environmental nutrient loading. We measure these effects as P loss in runoff. The methods that we employ in our current analysis are outlined below.

Environmental Nutrient Loading

Given the growing focus on P loading risks from agricultural operations in high concentration dairy producing areas and recent advances in the development of techniques useful for analyzing these risks, we necessarily base our environmental analysis for the regional animal feeding operation on the assessment of P loss in runoff. We, however, are also able to include in our analysis an assessment of the potential for N loading associated with the farm management adjustments. This is made possible by the availability of derived equations and data for estimating N runoff and leaching specific for soils in our agricultural production region (Boisvert, *et. al*, 1997). We examine the effects on P and N loading in our model using two distinct techniques for determining the distributions of phosphorus and nitrogen residuals from crop land.

To quantify the amounts of P lost to the environment due to farm nutrient management practices, we follow methods developed very recently in Vadas *et al*., (2009). According to Vadas *et al*., (2009), these modified methods that can reliably quantify field-level losses of P in runoff from surface-applied manure and fertilizer for a variety of soil types, crop and fertilizer management patterns, and geo-climatic conditions are compatible with and attempt to update the procedure used for ground water quality assessment models such as the Erosion-Productivity Impact Calculator (EPIC) model. In contrast, our estimates of nitrate loading make use of derived equations from Boisvert, *et al*., (1997) that relate nitrate loading from corn production to soil characteristics, weather, crop rotations and fertilizer application methods using nitrate runoff and leachate data generated from GLEAMS for specific New York soils.

We incorporate solutions to our nonlinear programming model into the abstractions of the known relationships between nutrient application, land vegetative cover and soil characteristics, weather, and nutrient loading. The application rates of manure and fertilizer phosphorus and nitrogen reflect the relevant dairy operators' decisions on cropping and nutrient management. Changes in these rates and in the patterns of crop production reflect the farm management responses to changing input and output prices, and to restrictions on land nutrient application. Land nutrient application rates differ in our model by the crops grown on CAFO land (i.e., corn grain, corn silage, alfalfa or orchard grass); the position of the current (corn) crop in the rotation (i.e., whether corn follows other corn, alfalfa or orchard grass in rotations); classification of the land based on crop productivity (i.e., low; medium, or high); and levels of STP (i.e., low; medium, or high). We estimate P and N runoff and leaching for corn fields only, thereby placing a more conservative limit on our total estimates (i.e., they do not include loadings from alfalfa or orchard grass).[21]

Phosphorus Runoff

Many studies have attempted to assess field level losses of phosphorus from agricultural land based on soil characteristics and applied manure, compost and fertilizers (see for example, Davis, *et al*., 2005; Sharpley and Moyer, 2000; Sharpley, *et al*., 2001; and Vadas, *et al*., 2008). The more recent studies make use of some notion of P runoff indexes that account for differences in nutrient management practices, soil characteristics and geographical and agro-climatic conditions, and rank the potential for P loss from agricultural fields. Sharpley, *et al*., (2003) for example, reports that 47 states had used a PI approach by 2003 and most had adapted the PI to local conditions and policy. A drawback to P indexes however is that their use mostly does not allow for explicitly quantifying P loss thereby posing a challenge to the planning of P loss reduction for agricultural fields. Process-based simulation models address these concerns in that they can quantify field-level losses of P in runoff but are considered difficult to use for routine management purposes and require excessive amounts of field-specific data (Vadas, *et al*., 2009)

[21] The methods in Boisvert *et al*. (1997) that we follow for estimating nitrate loadings do not account for runoff and leaching from alfalfa fields. Since no fertilizer N is added, and nitrogen-fixation further reduces N that is available for runoff from alfalfa, this omission may not be of serious consequence. Further, P loss may not be as important on alfalfa (see e.g., Ketterings *et al*., 2006).

New techniques developed by Vadas, *et al*., (2009) offer an improvement on the indexation methods without requiring the expertise or additional data associated with the process-based models. Their methods were validated against data from several independent published field studies and are useful for predicting annual dissolved P in runoff from surface-applied manure and fertilizers. We follow their general method in our estimation of phosphorus loss in runoff but the focus of our study is on the marginal changes in nutrient loadings attributable to differences only in field nutrient management in response to agricultural input and output prices and to CAFO regulations. Thus, we can ignore without consequence, the determination of P runoff losses that are a function of the soil characteristics or erosion factors.[22] We thus restrict our adoption of the models by Vadas, *et al*., (2009) to the estimation of P loss in runoff from manure and fertilizers.

We incorporate our solutions from the nonlinear programming model that represent the optimal nutrient management decisions of the CAFO into the relationships between land nutrient application, weather incidences and environmental loading. We make use of available data on soil characteristics and weather events for our selected three-county region in New York.

Estimation of P Runoff from Manure

For our modeling purposes, dissolved P in runoff from applied manure is estimated as in equation (2.2):

$$ROP_{man} = 0.4 * PR_{man} * PDF_{man} * \left(RO/PPT\right) \qquad (2.2)$$

[22] It is reasonable to assume that the land nutrient management factors are the only relevant variables from the no-policy to the nutrient regulations scenario. Soil characteristics such as initial soil nutrient status and topography are constant.

where ROP_{man} is the amount of dissolved phosphorus lost in runoff from manure in a rainstorm event (lbs/ac.); PR_{man} is P released from applied manure (lbs/ac.) and is the amount of dissolved P leached out of manure particles by precipitation during an event; PDF_{man} is a factor for manure application that distributes released P between runoff and infiltration, and it ranges between 0.0 and 1.0; RO is the precipitation runoff (in.) from the relevant storm incidence; and PPT is the measured amount of precipitation from the storm event (in.). PR_{man} is further defined as P available for runoff from the applied manure in water extractable phosphorus (WEP) and non-WEP forms. All P that is in non-WEP form at the time of manure application is unavailable for runoff at that time. According to Vadas, *et al*. (2009), 40 percent of applied manure WEP is available for direct loss to runoff from applied liquid manures and 10 percent of non-WEP becomes mineralized and available through the year. In our model, the estimates of total P produced in manure for the various fed rations come from the CPM-Dairy program output and are for all manure P that is available for plant uptake. The data do not distinguish manure WEP from non-WEP and we assume in our model that 40 percent of total manure P is available for direct runoff in a storm event.

The manure P distribution factor is determined as follows in equation (2.3):

$$PDF_{man} = \left(RO/PPT\right)^{0.225} \qquad (2.3)$$

where PDF_{man} is the manure distribution factor and RO and PPT are the runoff and precipitation variables, respectively, as defined above in equation (2.2). We adopt the curve number method developed by the Natural Resources Conservation Service (NRCS) to predict RO, the amount of precipitation runoff from fields (NRCS, 2003b). The curve number method uses empirically-determined mathematical relationships and appropriate values read off a curve number chart in the prediction of runoff. Its suitability for use in models that estimate P-runoff from variable source areas has been questioned (see Easton, et al., 2007). Notwithstanding, the results of our study do not account for spatial distribution of P runoff within the context of the cropland available to the dairy farm, thus making the curve number approach suitable for our purpose.

Our estimation of the field runoff from precipitation follows equation (2.4):

$$RO = \left(PPT - 0.2 \cdot S\right)^2 \Big/ \left(PPT + 0.8 \cdot S\right) \qquad (2.4)$$

where *RO* is the depth of runoff from the cornfields (in.) and is measured as rainfall in excess of the soil's capacity for infiltration. It depends on the intensity of rainfall as well as on such field characteristics as land use type, vegetative cover, and soil hydrologic group. *PPT* is the observed depth of rainfall for a single storm incidence in inches as earlier defined; and *S* is the depth (inches), of effective available storage on the fields.

Further, *S* is determined following equation (2.5):

$$S = \left(1000/CN\right) - 10 \qquad (2.5)$$

where *S* is the effective storage capacity of the field and *CN* is the curve number. The *CN* is read off the appropriate NRCS charts (NRCS, 2003b). It varies by soil hydrologic group, as well as by land use type. The latter distinction does not occur in our model as all of the fields for which we calculate P runoff loss are agricultural plots with row (corn) crops. However, following available soil survey data for the New York agricultural production region that our representative farm model captures, we identify soil hydrologic groups A, B, and C and the proportions of croplands on the representative farm that belong to each of these groups (see Table 4 in Boisvert, *et. al*., 1997). Our estimation of the P runoff thus accounts for the soil hydrologic groups.

Estimation of P Runoff from Commercial Fertilizers

The estimation of phosphorus runoff from fertilizers applied is similar to that for P loss from manure in equations (2.2) through (2.5), with some modifications. Estimation of the amount of dissolved P in runoff from applied fertilizers follows equation (2.6):

$$ROP_{fer} = PR_{fer} * PDF_{fer} * (RO/PPT) \qquad (2.6)$$

where ROP_{fer} is the amount of dissolved phosphorus lost in runoff from fertilizer in a rainstorm event (lbs/ac.); PR_{fer} is P released from applied fertilizer (lbs/ac.) and is the amount of dissolved P leached out of fertilizer by precipitation during an event. It includes all of the P applied in fertilizer form. PDF_{fer} is a fertilizer distribution factor which estimation is defined shortly; *RO* and *PPT* are runoff and precipitation (in.) as defined above.

The fertilizer P distribution factor is determined as in equation (2.7):

$$PDF_{fer} = 0.034 * \exp[3.4 * (RO/PPT)] \qquad (2.7)$$

where PDF_{fer} is the fertilizer distribution factor and lies between 0.0 and 1.0; and *RO* and *PPT* are the runoff and precipitation variables as defined. RO is as determined in equation (2.4).

Incorporating P Runoff into the NLP Model

Solutions to our nonlinear programming (NLP) model are substituted into the equations for estimating P loss in runoff as values for the amount of P available for release from applied manure and fertilizers (i.e. PR_{man} and PR_{fer} in the P runoff equations). Since fertilizer and manure application rates potentially differ by cropping activity (i.e., by land capability class, crops grown, position of cropping in rotations and in the CAFO regulations case, restrictions on land nutrient application), we necessarily apply equations (2.2) through (2.7) to each cropping activity that comes into the NLP solution. Further, we evaluate the equations for each of three particular measures of rainfall in any year and for 30 years of weather observations. The total P runoff for any cropping activity in any given year is calculated as the sum of residual P associated with manure and with fertilizer application and accumulates P lost to runoff through the storm incidences occurring in that year.

Total annual P runoff for individual cropping activities cumulatively sum up the runoff P associated with each of the storm events. This is such that P leached out of applied manure or fertilizer in a first (second) storm incidence is no longer available for loss through runoff during a second (third) storm event. In particular, equations (2.2) and (2.6) can be re-written as in equations (2.8) and (2.9):

$$ROP_{man}^{t} = 0.4 * (PR_{man}^{t} - PR_{man}^{t-1}) * PDF_{man} * \left(RO/PPT\right) \qquad (2.8)$$

$$ROP_{fer}^{t} = \left(PR_{fer}^{t} - PR_{fer}^{t-1}\right) * PDF_{fer} * \left(RO/PPT\right) \qquad (2.9)$$

where ROP_{man}, ROP_{fer}, PR_{man}, PR_{fer}, PDF_{man}, PDF_{fer}, RO and PPT are defined as in equations (2.2) through (2.7). The superscript t represents the three rainfall observations that are relevant to our estimation [i.e., t = 1, 2 and 3 are measures of rainfall observed within the 14 days after planting, at the time of fertilizer application, and at the time of harvest, respectively (in.)].

We determine the cumulative sum of P runoff for a single cropping activity, from all weather incidences within the year or season as in Equation (2.10):

$$PRO_j = \sum_{t=1}^{3} ROP_{man}^{tj} + \sum_{t=1}^{3} ROP_{fer}^{tj} \qquad j= 1,\ldots, J \qquad (2.10)$$

where PRO_j is the amount of dissolved phosphorus lost in runoff (lbs/ac.) from manure and/or fertilizer application associated with cropping activity *j* over all storm events.

Total P runoff for all of the grown corn acres is then determined as:

$$TPRO = \sum_{j=1}^{J} \left(PRO_j * Ac_j \right) \qquad (2.11)$$

where *TRPO* is the amount of P runoff from manure and fertilizer application on all cropped corn acres (lbs) and Ac_j is the relevant number of crop acres (ac.).

Nitrate Runoff and Leaching

To determine the effects of new nutrient restrictions on nitrogen loading on our NY CAFO region, we predict potential levels of N runoff and leaching associated with the changes in land application of manure and fertilizer on corn acres. To do this, we make use of empirical techniques developed in Boisvert, et al. (1997). In that work, estimates of N runoff and leachate were obtained for different length corn rotations and fertilizer application rates using GLEAMS for 105 New York soils. The resulting data were then used to estimate equations relating nitrate runoff and leaching from corn production to soil characteristics, weather, rotations and fertilizer application, in translog functional form. The nutrient loading function is stated in its general form as:

$$\ln Y = \ln e_0 + \sum_{h=1}^{H} d_h D_h + \sum_{k=1}^{G} e_k \ln W_k + 1/2 \sum_{k=1}^{G} \sum_{l=1}^{G} f_{kl} \ln W_k W_l \qquad (2.12)$$

where Y is either nitrate runoff or leaching; d, e and f are the relevant parameters of the equation, D_h are dummy variables that take on the value of one if a soil is in hydrologic group h and zero otherwise; and W_k is the k^{th} of G variables representing soil characteristics, cropping practices and weather factors. The set of recursive equations for estimating nitrate runoff and leaching are presented in detail in Appendix 1 (Chapter 1). Nitrate runoff appears as an explanatory variable in the leaching equations to account for the fact that increased surface runoff leaves less N to leach from the soil. Dummy variables account for differences in the hydrologic groups of the soils A, B and C. Soils in group C have potential for higher runoff as they are heavier and have greater slope.

In evaluating programming model solutions, we allow to change in the nitrate loading equations only the values for those variables that are directly related to soil nutrient management; i.e., manure and fertilizer application. The means and regression coefficients for all other variables are assumed constant. Field characteristics such as the slope, soil horizon depth, N mineralization rates, organic matter content and erodibility are assumed to take on the mean values for the region and do not change with cropping patterns. We allow for the effects of variation in weather by evaluating the regression equations for a sample of historical weather observations. We keep the nutrient management variables constant for any single weather observation, thereby restricting variations in weather across the fields. Our sample of weather observations consists of actual weather data for New York State counties (Boisvert, et al., 1997).

Empirical Results

The Base Model

Feed prices experienced by dairy farmers in the Northeast reached a decade-long high in 2008 (NASS, 1991-2009). While the prices moderated somewhat in the following year, feed costs remain considerably above historical levels. To account for the most recent general elevation in feed prices while basing our analysis on a price set that may be more sustainable into the near future we make use of the most recent available 5-year average prices (i.e. 2005-2009) as the relevant starting coefficients. At the 5-year average prices for production input and output; it is optimum for the regional model farm to raise the maximum of the 724 cows and 564 replacement heifers allowed. The milking cows are fed a corn silage-base ration that contains 10 percent DDGS [on a dry matter (DM) basis] with an 8 percent fat content. Dry cows are similarly fed a ration with 10 percent DDGS (8 percent fat) while heifers are fed a ration with 13 percent dry matter DDGS (8 percent fat).

Corn (grain and silage) and alfalfa are grown, with half of the available CAFO acres devoted to each crop. Orchard grass is not grown on the farm but is purchased for inclusion in the total mixed ration fed. Although corn is grown, some additional corn grain is purchased to supplement that fed to the animals. Alfalfa grown on the farm is both fed to the farm animals and sold.

All manure produced by the farm animals is applied to the land as nutrients. The crop nitrogen requirements are met so that no nitrogen fertilizer is purchased beyond that which is needed as starter side-dress N. Also, no phosphorus fertilizers are purchased. Revenues and costs associated with the farm animal and crop production (including nutrient management) and feeding and crop sales decisions are presented in Table 2.3. To ease side-by-side comparisons of the base and policy scenarios, we include in Table 2.3 solutions to a relevant nutrient restrictions scenario that we discuss in a later section.

Production Costs and Revenues

In Table 2.3 we summarize the major revenues and costs associated with the base simulation of the regional dairy farm management decisions. No nutrient standards are in effect for this simulation. The farm receives $3,752 per cow in total receipts from crop, livestock and milk sales (less payment made for milk marketing). Milk sales are expectedly the biggest income source at 87 percent of all farm proceeds. Up to 69 percent of the gross farm revenue is expended as production costs, with the largest proportion of the farm budget going to the purchases of feed (i.e., $1,046 per cow). Manure and nutrient management costs are only a fraction of the total production outlay.[23] As we show later, nutrient management is a more important cost for the model simulations that include restrictions on land nutrient application. Field manure applications make up about three-quarters of the manure and fertilizer-related costs for the farm in the base scenario.

No fertilizer N (excluding starter N) or P is purchased and manure is not shipped off to land not controlled by CAFOs so that the off-farm manure transportation costs are not important. Alternative DDGS costs are however relevant for the base model solutions.

[23] Manure and nutrient management costs include the cost of spreading manure on land, purchasing and spreading fertilizers; and in the policy case, disposal of excess manure off-site.

Table 2.3: Net annual revenues, receipts and costs for CAFOs in the three-county region: **Base** and **Policy** scenarios

	Base Solution (No Policy)	Policy Solution (Nutrient Standards)	Percent Change[6]
Net annual revenue	1,153	1,104	(4.44)
Total receipts	3,752	3,752	0.00
Milk	3,279	3,279	0.00
Crop sales	200	200	0.00
Livestock sales	273	273	0.00
Total Costs	2,599	2,648	1.85
Feed	1,046	1,046	0.00
Labor	589	573	(2.79)
Livestock production[1]	535	535	0.00
Crop production[2]	270	270	0.00
Other production costs[3]	112	112	0.00
Nutrient management	47	112	58.04
Manure spreading	35	16	(118.75)
Offsite disposal[4]	0	64	-
P fertilizer purchase	0	9	-
N fertilizer purchase	12	12	0.00
K fertilizer purchase[5]	0	11	-

[1] Less labor and feed. Includes utilities, supplies, repairs and maintenance.
[2] Less labor and crop fertilization costs. Includes custom lime, seeds, herbicides and soil testing.
[3] Includes purchases of gasoline and diesel fuel for on-farm use.
[4] Off-site manure disposal cost is $4/ton.
[5] The model assumes that up to 4 lbs/ac of potassium is available in manure. Crops' demand in excess of K available in manure is purchased.
[6] Percent changes in values from base to no-policy scenarios; negative values in parenthesis.

Effects of DDGS Prices

We report relevant programming solutions for given relative prices of DDGS in Table 2.4. The prices of DDGS are reported in relation to average corn prices for year 2008 (i.e. $234.7/ton for corn grain). The relevant DDGS-to-corn price ratios that we examine range from 0.18 to 1.60. Five of the solution sets that we report are the programming solutions obtained when the optimal dairy management solution changes in response to the change in DDGS prices. The other two are solution sets at 2008 and

5-year average DDGS prices, respectively (i.e. DDGS-to-corn price ratios of 0.60-to-1 and 0.49-to-1, respectively), that we report to provide context to the discussions of the nonlinear programming solutions (see Table 2.4).

As DDGS prices are allowed to change relative to other feed prices, the combined demand for (8 and 12% fat-) DDGS also changes. The optimal numbers of animals do not change as the relative prices and utilization of other feed ingredients to DDGS changes, although the amounts fed of the bio-fuel byproducts vary. As expected, a greater proportion of the animals are fed with rations that include DDGS as its relative price falls. For example, while no DDGS is fed when the DDGS-to-corn price ratio is 1.60-to-1, 100 percent of the animals are fed some DDGS in rations when the price ratio is reduced to 0.55:1 and lower. However, as more DDGS is fed, N and P levels are increased in the rations fed and the amounts of nitrogen and phosphorus available in the manure increase.

As shown in Table 2.4, 71 pounds of manure phosphorus are produced per cow per year when no DDGS is fed, compared to 84 pounds of P produced per cow when the DDGS-to-corn price ratio is 0.18:1. In the case of nitrogen, the relevant numbers are 179 and 202 pounds per cow per year, respectively. The increased availability (reduced relative prices) of lower cost feed ingredients lead to their expanded inclusion in the TMR and to increased cost savings where there are no restrictions to land manure application. However, higher levels of phosphorus and nitrates in the manure raise the risks of nutrient loss in runoff to the environment. According to our model, field P is applied on corn at 40 pounds/acre when the DDGS-to-corn ratio is 1:60: 1. Phosphorus loss in runoff from corn fields is 5.9 pounds/acre on average at this price level. At the 0.60:1 price ratio, 49 pounds per acre of P is applied on corn and average P loading to the environment from corn fields increases to 7.2 pounds per acre.

Table 2.4: Feeding, nutrient management and environmental loading with alternative DDGS prices for CAFOs in the three-county region: **Base** scenario

Price ratio[1]	1.60	1.56	1.19	0.60	0.55	0.49	0.18
Net revenue ($/cow)	1,068	1,069	1,080	1,130	1,137	1,153	1,244
Rations fed[2] (% cows):							
CS	100	100	100	100	0	0	0
CS1210	0	0	0	0	100	100	2
ALF0820	0	0	0	0	0	0	98
DC	100	0	0	0	0	0	0
DC8	0	100	100	100	100	100	100
Hef	100	100	0	0	0	0	0
Hef8	0	0	100	100	100	100	100
Manure produced (tons/cow)	29.2	29.2	29.2	29.2	29.3	29.3	29.3
P in manure (lbs/cow/yr)	71	73	77	77	77	77	84
N in manure (lbs/cow/yr)	179	177	177	177	183	183	202
P application on corn (lbs/ac.)	40	44	40	49	49	49	42
Manure P as % total P applied	100	100	100	100	100	100	100
P runoff loss from corn (lbs/ac.):							
Mean	5.9	6.5	5.9	7.2	7.2	7.2	6.0
Maximum	13.4	14.9	13.4	16.4	16.4	16.4	13.6
Std Deviation	4.2	4.7	4.2	5.1	5.1	5.1	4.2

[1] Ratio of the price of DDGS to the price of corn grain on a per ton basis (dry matter). To compute the DDGS price, multiply ratio by $234.7/ton. The price ratio of DDGS to corn in 2008 is 0.60:1 while the price ratio of DDGS for the 5-year period average (2005-2009) is 0.49:1.

[2] Ration headings are formatted by type of DDGS fed. DDGS were included in dry cows' rations at approx. 13% of total dry matter, heifers rations included DDGS at 10% of total dry matter, e.g., DC12 = dry cow ration with 12% fat DDGS, and RH8 = replacement heifer ration with 8% fat DDGS. DDGS are not fed for CS (corn silage), DC and Hef rations.

Results such as these indicate limited potential for DDGS in CAFO livestock rations when environmental concerns are considered. We discuss the environmental implications of the policy in more detail in a later section.

The Policy Scenario

We also use 5-year average prices (i.e. 2005-2009) as the relevant starting prices for the model simulating new restrictions on field nutrient application. At this price level, the results on rations fed and crops grown are the same as in the base case. Orchard grass is not grown on the farm, but is purchased for inclusion in the total mixed ration fed. Corn and alfalfa are each grown on about 50 percent of the available CAFO acres.[24] Additional corn is purchased to supplement animal feed and alfalfa grown on the farm is both fed to the farm animals and sold.

Importantly, we find that the constraints on field N or P applications from manure are binding so that only 45 percent of the manure produced by the farm animals is applied to the land as nutrients. The remainder of the produced manure must be disposed of off-farm. P (N) fertilizers are then purchased to make up for any shortfalls in meeting the crop P (N) needs. In our model, nitrogen fertilizer purchases over starter N are minimal at an average of one-tenth of a pound per acre. The purchase of phosphorus fertilizers however increases from zero in the base scenario to 12 pounds per acre on average with simulation of the policy.

The costs and incomes associated with the farm management in the nutrient policy scenario are shown in Table 2.3. Revenues accruing to the farm from crop, livestock and milk sales do not vary from the base case. Production costs, however, go up as costs are incurred for additional fertilizer purchases and for off-farm manure

[24] We show in a later section that this distribution of the land between the crops would change as it becomes costlier to transport excess manure off the farm.

disposal so that expected net income is reduced. Our simulations result in fertilizer P purchases of $9 per cow on average per year, while manure disposal adds another $64 per cow per year in costs.

The additional nutrient management costs are however accompanied by cost reductions elsewhere. The on-farm labor needs for manure application dampen, reducing the total expenditures for farm labor.[25] Non-labor costs associated with manure spreading are also reduced.

Our analysis indicates that the constraints on land application of N and P seriously limit on-farm field application of manure produced by the farm animals when N or P content in the manure is high. Further, although the inclusion of DDGS in the feed rations increases the levels of N and P in manure in our model, we find that the restrictions on land manure application are not sufficient to prevent the increased use of DDGS in feed rations when the relative price of DDGS falls. In particular, the feeding regime for the dairy cows and heifers remains the same from the no-policy to the policy scenarios. However, more of the manure produced on the farm need be shipped off the farm to meet with the new regulations so that net farm incomes fall with rising costs of off-farm manure disposal. We report the programming solutions for the base and policy scenarios for a given set of feed prices and estimates of the unit costs of off-site manure disposal in Table 2.5.

Effects of Manure Disposal Costs

The restrictions on land nutrient applications calls for off-site transportation of manure produced in excess of optimal levels necessary to meet crop needs. We analyzed dairy management adjustments over a range of manure disposal costs.

[25] The model does not directly account for farm labor that may be needed to spread manure on off-farm or manure disposal sites. The additional labor costs are instead assumed (implicitly) to be a component of the aggregate off-farm manure disposal costs.

Table 2.5: Manure and fertilizer management and environmental loading with alternative costs for off-site manure disposal in the three-county region: **Base** and **Policy** scenarios

Disposal Costs $/ton	Base Scenario	2	4[1]	6	8	10	12	14	16
Net revenue ($/cow)	1,153	1,137	1,104	1,073	1,041	1,011	982	952	923
Manure produced (tons/cow)	29	29	29	29	29	29	29	29	29
Disposed off-farm (%)	0	55	55	55	52	52	50	50	50
Nutrient management on corn:									
P application[2] (lbs/ac.)	49	32	32	32	26	26	15	15	15
Manure P (%)	100	63	64	64	71	71	90	90	90
N application[2] (lbs/ac.)	136	68	68	68	68	68	68	68	68
Manure N (%)	85	70	70	70	63	63	46	46	46
Field P loss in runoff from corn (lbs/ac.)									
Mean	7.2	3.4	3.4	3.4	3.0	3.0	2.0	2.0	2.0
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	16.4	9.1	9.1	9.1	7.6	7.6	4.8	4.8	4.8
Std. Deviation	5.1	2.6	2.6	2.6	2.2	2.2	1.5	1.5	1.5
Field N loss in runoff from corn (lbs/ac.)									
Mean	8.6	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Minimum	3.5	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Maximum	19.9	9.5	9.5	9.5	9.5	9.5	9.4	9.4	9.4
Std. Deviation	4.1	1.9	1.9	1.9	1.9	1.9	1.8	1.8	1.8

[1] The relevant policy scenario for comparison with the base case is for off-site manure disposal cost of $4/ton.

[2] Nutrient applications on corn acres. N applications include starter nitrogen.

As this management strategy is unlikely to be observed in practice, we restrict the presentation of the model solutions to the range of off-site manure disposal costs within which the animal feeding establishments maintain current levels of operation.[26] Manure and fertilizer application in the regional dairy model are compared for 8 policy scenarios that represent alternative costs for off-site manure disposal (see Table 2.5). We also include the base policy solutions in the table for comparison. Manure transportation costs start out at $2 per ton (i.e., 14 miles roundtrip if we assume $0.14/ton-mile) and go up to $16 per ton (i.e., 114 miles roundtrip).[27]

By way of comparison, the travel distances implied by our calculations are less than the maximum allowed distances (170 miles) for which manure-exporting farms participating in a poultry litter transportation program modeled for Virginia could receive subsidies (Pelletier, *et. al*., 2001). The relevant manure disposal cost for direct comparison with the base case in our model is $4 per ton.[28]

As shown in Figure 2.1, net incomes drop as the manure disposal costs increase. The expected net revenue is $1,137 per cow when manure disposal cost is $2 per ton and $923 per cow when the unit cost of off-farm manure disposal is $16. This represents an 11 percent drop in expected net farm incomes over the relevant range of manure disposal costs. To mitigate the effects of the increasing costs and associated losses to net farm income, less of the manure produced is taken off the farm as the off-farm manure transportation cost (distance) is increased (see Table 2.5).

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[26] Unlike the results in Hadrich, *et. al*., (2008) our model solutions did not include the reduction of DDGS in feed as a CAFO response to high manure disposal costs. Relatively lower P concentrations in DDGS in our model (i.e., than was allowed in Hadrich, *et. al*, 2008) drove this result. P levels in our formulation of DDGS rations using CPM-dairy program were constrained to maintain milk production levels and accommodate animal nutrient considerations.

[27] Per ton-mile estimates for dairy manure transportation calculated using Pelletier, *et al*. (2001); Feinerman, *et al*. (2004) and USDA indices of agricultural prices paid (NASS).

[28] In comparison, calculations we make based on other authors' estimates place manure disposal costs at $2.2/ton (Harrigan, 2001) and between $2.9 and $4.4/ton (Hadrich, *et al*., 2008). However, the Hadrich, *et al*., (2008) estimates are for travel distances not greater than 1 mile.

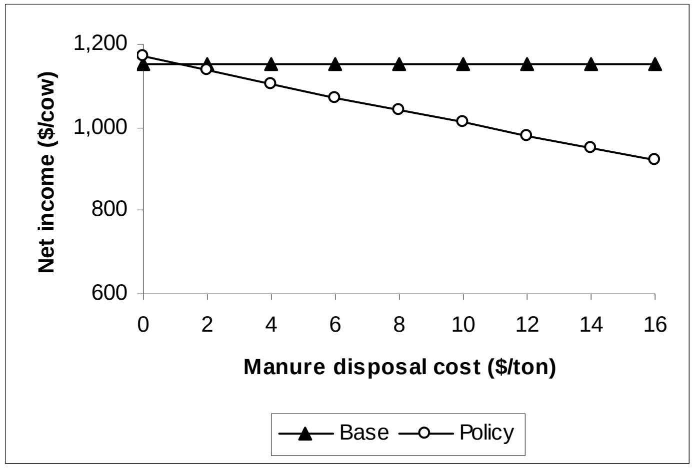

Figure 2.1. Net returns for alternative manure disposal costs

When the off-site manure disposal cost goes up from $2 per ton to $16 per ton, off-farm manure disposal drops from 55 percent of the volume of manure produced to 50 percent. Meanwhile, phosphorus application on corn is reduced on average by 53 percent over the range of manure disposal costs that we examine. As we show in the next section, nutrient management and land use adjustments on the dairy CAFOs underlie the changes observed in manure and P applications.

Effects on Cropland Use

Manure application may be more flexible on cropland growing alfalfa than on corn. We find in our model that the dairy management takes advantage of this flexibility, increasingly growing alfalfa on the less regulated land to avoid higher costs of transporting manure off the farm. The land use adjustments to increasing manure disposal costs under the nutrients policy scenario are shown in Table 2.6. More land is devoted to alfalfa as the management of excess manure nutrients becomes more costly. Specifically, 709 acres are devoted to each of corn and alfalfa at a $2 per ton off-site manure disposal cost.

Table 2.6: Land use by soil distribution for alternative manure disposal costs: **Base** and **Policy** Scenarios

MDC[1]	Base Scenario	2	4	6	8	10	12	14	16
Total acres cropped									
Corn	709	709	709	709	565	565	565	565	565
Alfalfa	709	709	709	709	853	853	853	853	853
Cropped acres by soil quality[2]:									
Corn Land 1	163	163	163	163	163	163	163	163	163
Corn Land 2	468	468	468	468	324	324	324	324	324
Corn Land 3	78	78	78	78	78	78	78	78	78
Alf Land 1	163	163	163	163	163	163	163	163	163
Alf Land 2	468	468	468	468	612	612	612	612	612
Alf Land 3	78	78	78	78	78	78	78	78	78
Cropped acres by agronomic soil test P (STP) levels[3]:									
Corn[4]:									
High STP	50	92	103	103	103	103	103	103	103
Medium STP	376	85	74	74	160	160	404	404	404
Low STP	283	532	532	532	302	302	59	59	59
Alfalfa[4]:									
High STP	50	11	0	0	0	0	0	0	0
Medium STP	376	662	674	674	587	587	344	344	344
Low STP	283	36	36	36	266	266	509	509	509

[1] MDC is manure disposal cost in $/ton. The relevant policy scenario for comparison is that for $4/ton off-site manure disposal cost.
[2] Land classes 1, 2, and 3 are low, medium and high corn silage yield potential, respectively (i.e. 4.9, 5.3 and 5.9 tons/acre respectively).
[3] Low STP soils have less than 9 lbs/acre, medium P soils have 9 – 39 lbs/ac and high P soils have more than 40 lbs/acre of soil Morgan P
[4] Since P is not restricted, STP distinctions are not relevant for the base case. Cropped acreages reported follow the soil distributions.

However, upwards of $8 per ton, only 40 percent of the land is left in corn and alfalfa cropping increases to 853 acres. To achieve this change in land use, the medium quality (i.e., based on soil corn silage yield potential) and low P (i.e., based on soil agronomic P testing) lands are switched from corn to alfalfa (see Table 2.6). Since they can receive more manure or fertilizer P according to the regulations, the low P soils become more important for spreading manure than for grain production as manure disposal costs rise.[29] Further, more alfalfa is grown on the low P soils as alfalfa has higher potential for receiving the manure produced on-farm. At $2 per ton for manure disposal, corn (alfalfa) is grown on 523 acres (36 acres) of the low STP soils. As the manure disposal costs increase to $12 per ton however, corn (alfalfa) growing is reduced (increased) on the low P soils to 59 (509) acres.

Effects on Field Applications of Manure and Fertilizer

We find that while manure nutrients are applied to all of the corn acres in the base case, 76 percent of corn land receives manure under new nutrient regulatory conditions.[30] Minimal use of nitrogen fertilizers (beyond starter N) is reflected for our model in that zero and 2 percent of the corn land receive commercial N fertilizer under the base and policy scenarios, respectively. No fertilizer P or N is purchased for use on alfalfa. However, at least some manure is applied on 100 percent of land growing alfalfa under both scenarios (see Table 2.7).

The optimal field manure application rate in the base case is 18.6 tons per acre on average for corn and 11.4 tons per acre on average for alfalfa. In the model simulation of the nutrient restrictions, the average manure application rates fall to 7.6

[29] After accounting for P inherent in the soil, low P soils require on average, 40 lbs/ac. of manure or fertilizer P for corn production, and 30 lbs/ac. for alfalfa; Medium P soils require 15lbs/ac. on average for corn and alfalfa; while high P soils have no additional P requirements.
[30] The relevant solution set for the base case uses 5-year average prices for DDGS. The relevant policy simulation assumes $4/ton for off-site manure disposal costs.

tons per acre on corn and 6.0 tons per acre on alfalfa. Manure P and N application are reduced on corn and alfalfa fields. While fertilizer P applications increase on corn with the policy, the sum of all P applied is reduced. Total field applications of manure and fertilizer nitrogen and phosphorus are thus reduced with the simulation of the new nutrient standards.

Table 2.7: Manure and nutrient management on corn and alfalfa: **Base** and **Policy** scenarios

	Base Solution (No Policy)	Policy Solution (Nutrient Standards)[1]
Manure and fertilizer applications (Percent of acres covered):		
Corn grain and silage:		
Manure	100	76
Fertilizer P	0	2
Fertilizer N	0	85
Alfalfa hay:		
Manure	100	100
Fertilizer P	0	0
Fertilizer N	0	0
Manure and fertilizer applications (per acre):		
Corn grain and silage:		
Manure (tons)	18.6	7.6
P as manure (lbs)	49	20
P as fertilizer (lbs)	0	12
N as manure (lbs)	116	47
N as fertilizer[2] (lbs)	20	20
Alfalfa hay:		
Manure (tons)	11.37	6.0
P as manure (lbs)	30	16
P as fertilizer (lbs)	0	0
N as manure (lbs)	71	37
N as fertilizer[1] (lbs)	0	0

[1] The relevant policy scenario for comparison with the base case is the model simulation for off-site manure disposal cost of $4/ton.
[2] Includes purchase of 20 lbs/ac of pre-sidedress nitrogen.

Shadow Prices of Land

The crop production and nutrient management adjustments to the new nutrient standards have important implications for land economic value and from a nutrient loading perspective. As demonstrated using mathematical equations and a stylized example (in Appendix 2), crop land on CAFOs have value both for crop production and as manure receiving sites. We find in our policy model that the value of the unrestricted land controlled by CAFOs rises relative to the other land classifications as the costs of off-site manure disposal increases (Figure 2.2).

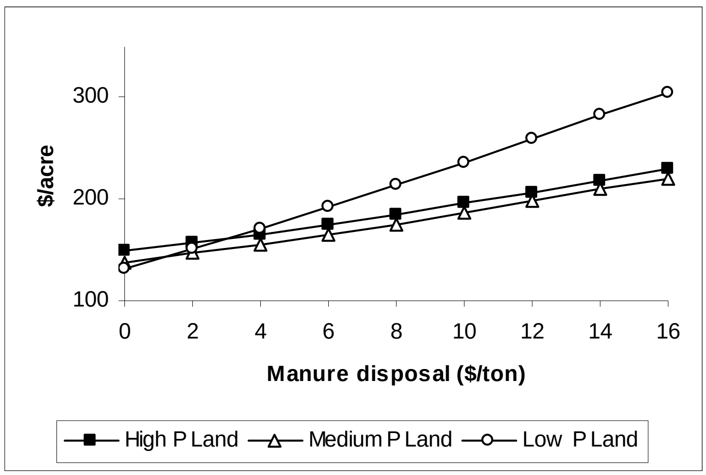

Figure 2.2. Shadow value of land under nutrient policy

At minimal manure disposal costs (i.e. zero to $2/ton), the value of land for cropping is the dominant land value component so that soils with higher P content are more attractive from a crop production stand point. As the manure disposal costs increase, however, the value of being able to apply manure nutrients on the land becomes more important. Low soil P land is as valuable as medium soil P land at $2 per ton manure disposal costs and surpasses all other groups at off-farm manure shipping costs beyond $4 per ton. As the manure disposal costs increases, the marginal value of low P soils increase relative to medium and high STP land.

Field Loss of Nutrients in Runoff

Environmental standards could specify target levels of pollution that relevant polluters receive disincentives for exceeding (e.g., graduated taxes), or maximum allowable levels above which offenders pay fixed penalties (Bunn, 1999). When applied to environmental policy regarding agricultural production, structuring the environmental restrictions in this manner would encourage agricultural producers whose operations have significant impacts on environmental quality to take the environmental pollution outcome into consideration in their production and other farm management decisions. From a modeling perspective, environmental regulations that so specify target or threshold levels of pollution necessitate or allow for the explicit inclusion in the mathematical programming models of the decision-maker, safety-first constraints to production (see for example, Qui, *et al.*, 2001).

The CAFO regulations on environmental pollution in New York that we analyze, rather than specify threshold levels on nutrient loading from dairy operations, are designed to directly regulate the land application of nutrients, thus reducing the environmental risks from the source. As such, animal feeding operations need not consider final (environmental quality) outcomes of their activities in their management decisions and programming models of the decision-making entity need not explicitly include production effects on nutrient loading. Instead, P and N runoff loss associated with farm animal and crop production can be conveniently assessed ex-post.

Our work uses historical data on weather for the dairy producing regions for the ex-post analysis of production effects on environmental quality. By linking the differential levels of manure and fertilizer applications associated with the relevant base and policy scenarios to actual weather data, we obtain for a 30-year period, empirical distributions of P and N loading for the three-county region. For the base (policy) scenario, observed variations in P and N losses for the 30 weather data points are due strictly to differences in weather. Given the empirical distributions, we can isolate potential effects of the policy by comparing simple statistics of the distributions; e.g., the means and standard deviations, for the base versus the policy simulations. We include this approach in our analysis of the results.

The estimates of average rates of P and N field losses are important for providing general approximations of the nutrient loading levels associated with production in the region and the extent to which the new nutrient policy would reduce these estimations.[31] We find that the mean rate of P loss in runoff from the corn fields for our sample of 30 weather observations is 7.2 pounds per acre in the base case, and 3.4 pounds per acre under the nutrient regulations. This represents a policy-induced reduction in average P loading per acre of 53 percent. P runoff associated with the highest amount of rainfall in the sample is 16.43 pounds per acre in the base case, with simulation of the nutrient policy reducing this measure of P loading by 43 percent. In the case of nitrogen loss to the environment the average nitrate loading rate is 8.6 pounds per acre for the base scenario and 4.5 pounds per acre under the policy simulation.

However, the estimates of nutrient loading that are more important from an environmental quality perspective are the nutrient losses associated with severe weather incidences. A safety-first component is included in our ex-post analysis of the implications of CAFO regulations for environmental quality. It is useful for assessing

[31] Recall that we focus on the marginal changes in P and N runoff, ignoring nutrient losses not directly attributed to fertilizer and manure applications so that our P and N runoff estimates are conservative.

the extent to which the new nutrient restrictions can limit extreme cases of P and N loading.

A Safety-First Approach to Nutrient Loading

The effect of the new nutrient policy on reducing nutrient loading to the environment can be determined by examining P runoff and N runoff and leaching losses associated with (known) probabilities of extreme weather. The safety-first approach that we adopt is outlined formally for P and N loss in runoff:

$$\Pr(P_{RO} > P_W) \leq W \qquad (2.13)$$

$$\Pr(N_{RO} > N_W) \leq W \qquad (2.14)$$

where the expressions in Equations (2.13) and (2.14) denote that the probability that some P (N) runoff (and leaching) relationship holds is not greater than an exogenously-determined level (*W*). P_{RO} (N_{RO}) is the average annual loss of P (N) in runoff (and leaching) from all corn fields in pounds per acre. *W* is the probability of extreme storms occurring and ranges between zero and one. This value can be set by the regulatory entity for reasonable assumptions of what constitute severe precipitation incidences and to reflect historical weather in the region. P_W (N_W) is obtained from P (N) loading estimations for the sample of 30 weather observations and is the average P (N) loss in runoff (and leaching) from all cornfields that corresponds to *W*. For the purpose of assessing environmental regulation, P_W (N_W) would indicate the lower limit on the amount of P (N) runoff that occurs for a set level of probability. An efficient environmental quality policy should dampen this value by a significant amount. Levels of P_W (N_W) are compared in our analysis for the base and policy scenarios.[32]

Our analysis involves comparing the P (N) distributions for the base and policy scenarios by plotting the estimates of P (N) loss in runoff associated with the model simulations against the probabilities of their occurrence given the sample of weather data. The cumulative probability for all the data observations is one. Before the distributions are plotted, the estimates of P runoff are ranked (given weather incidences) from low to high for the base and the policy scenarios as in Figure 2.3.

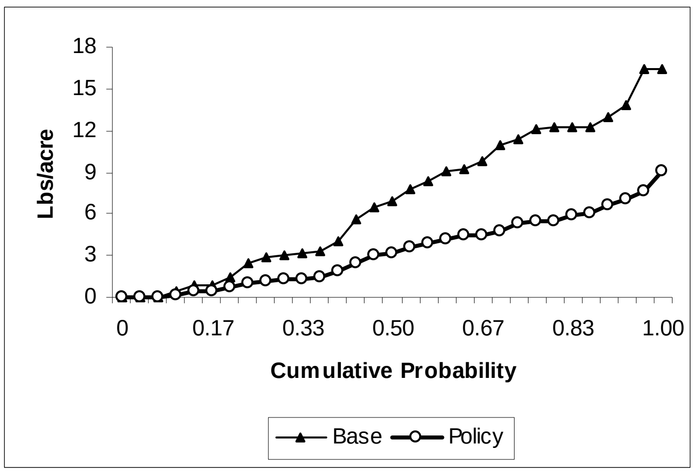

Figure 2.3. Phosphorus loss in runoff from corn fields

Similarly, cumulative distributions of nitrate runoff and leaching are plotted for the base and nutrient regulations scenarios as in Figure 2.4. Environmental quality improvement following regulations on land nutrient applications is evident for our analysis by the distribution of P (N) runoff for the policy case lying below that for the base case throughout; i.e., the P (N) estimates of runoff (and leaching) associated with the ranked weather observations are always lower in the policy than in the base case.

[32] The relevant policy scenario for comparison is $4/ton off-site manure disposal cost.

To introduce a safety-first interpretation to the model results, we assume an arbitrary cut-off of 10 percent for the probability of extreme weather occurring; i.e., *W* is 0.10 in Equations (2.13) and (2.14). In Figure 2.3 and Figure 2.4, this point is 0.90 on the horizontal axis.

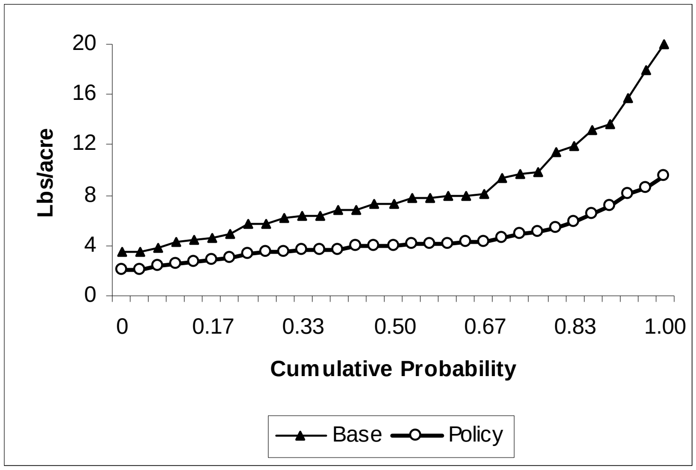

Figure 2.4. Nitrate loss in runoff and leaching from corn fields

Reading (off the vertical axes) the nutrient loading estimates that correspond to this point for the base and policy runoff distributions gives us the lower limits on the amounts of nutrient runoff losses that could only occur with a 10 percent probability (i.e., $P_W \mid W = 0.1$). Given this interpretation, the limit on P runoff that is exceeded not more than 10 percent of the time (in the base case) is 12.9 pounds per acre. The analogous threshold runoff for the nutrients standards scenario is 6.6 pounds of phosphorus per acre. While the results suggest that the new nutrient restrictions reduce P loading on average, they also indicate that significant risks of P runoff could remain during severe storm events. Restricting land nutrient applications to the agronomic soil uptake rates also leads to reduced amounts of nitrate loss in runoff and leaching. As deduced from Figure 2.4, the level of nitrate loading that is exceeded not more than 10 percent of the time (according to our sample of weather data) is 13.6 pounds per acre in the base case, and 7.1 pounds N per acre under the policy simulation. However, as with P loading, these results may indicate that there still remain significant risks of nitrate loss to the environment when severe storms occur.

Long-run Effects of Nutrient Restrictions Policy

Our analysis does not account for the long-run effects of the new nutrient applications on regional land and environmental quality. However, we can offer some comments on the likely implications given the current results.

As CAFOs follow the nutrient restrictions policy, fewer nutrients are applied in excess of the soil-crop nutrient requirements. It is reasonable to expect that soil P levels would be reduced on average in the long run, particularly for high P soils where additional P applications are not allowed under the regulations on land nutrient applications. The distributions of regional land over the three STP classes could thus change over time, with much of the (currently) high STP land becoming re-categorized as of lower soil P status. On the other hand, successive additions of manure and or fertilizers to lower P soils could raise the P levels on those soils so that all soils converge over time. This scenario could have a number of implications.

First, the most important gains for surface and ground water quality (from the policy) could occur in the short run. Since P levels are markedly reduced with the onset of the policy, future improvements in environmental quality are likely to be more modest. Second, as P levels are reduced on higher P soils, and lower P soils lose their enhanced values as manure disposal sites, land internal values should converge (to medium or average soil P levels) for croplands of the various soil test categories.

Conclusions

Regional mathematical programming models were developed to assess the implications of new nutrient standards for land nutrient application on confined animal feeding operations (CAFOs) in New York. We explicitly accounted for CAFO regulations on field manure and fertilizer applications to analyze the effects on measured outcomes of the farm management adjustments to the new nutrient policy and to recent changes in relevant agricultural prices. Our mathematical programming methods and the availability of a set of unique data allowed us to assess the policy effects on farm income, land use, manure and fertilizer management, and environmental quality for a three-county dairy production region in New York. Our mathematical methods also allowed for the assessment of the differential effects on internal land values, of the new CAFO nutrient restrictions and alternative manure disposal costs. In particular, we used a mathematical treatment of the Kuhn-Tucker conditions derived from the dairy CAFO optimization problem and a stylized case of the model solutions to determine how land economic values differed given crop production and manure-application potential.

In response to high prices of traditional feed ingredients, our model solutions indicated the potential for inclusion of unconventional feed ingredients such as distillers dried grains and solubles (DDGS) in livestock rations. From our model results, these ration adjustments on regulated dairy CAFOs increased the levels of nitrogen and phosphorus in the dairy waste, and where manure was applied on fields as crop nutrients, nutrient applications exceeded levels required for optimum crop yield, increasing the risks of environmental nutrient loading. Given our modeling of the new policy and our initial assumptions on resources available to CAFOs in the dairy producing region, our results further indicated that the land nutrient regulations mitigate the excess nutrient problem. However, while the new regulations reduced nutrient loadings on average, there were indications that significant risks of nutrient loss to the environment could remain for severe weather incidences. Our results also indicated some losses in farm income for regulated CAFOs.

The new nutrient restrictions required that more than half of the manure produced on CAFOs in the dairy-producing region was transported off-site for disposal. Since off-farm manure disposal costs and the overall dairy operating costs are expected to rise as the CAFOs travel longer distances to find manure-receiving locations, net farm income was sensitive to the implied assumptions on the availability of nearby land suitable for manure disposal. To mitigate the income losses from higher off-site manure disposal costs, the dairy management took advantage of flexibilities in the nutrients regulation by growing more alfalfa than corn on soils that could receive more manure under the regulation. Alfalfa provided more conducive conditions for spreading manure because of its inherent agronomic characteristics. Alfalfa thus increased in field crop value when the dairy farm management faced the stricter regulations on manure application and higher costs for transporting excess manure off the farm.

Our analysis of the land shadow values demonstrated that crop land on regulated CAFOs had differential value as crop production and manure-receiving sites, with croplands with lower levels of agronomic soil test phosphorus (STP) taking on enhanced value for manure disposal. The effect of the nutrient policy on CAFO land was more pronounced as the costs of off-site manure disposal costs increased. In particular, as the manure disposal costs increased, the shadow prices of the low STP soils (that allowed for substantial manure application) controlled by CAFOs increased significantly in relation to land on which no or minimal P applications were allowed.

Overall, results from our analysis - the sensitivity of CAFO incomes to manure disposal costs in particular - could indicate that greater oversight may be required for environmental quality gains to be realized from the new field nutrient regulations for concentrated animal feeding operations.

APPENDIX 2.A

ANALYSIS OF LAND INTERNAL VALUE:

THE STYLIZED NON LINEAR PROGRAMMING MODEL

The new policy on field nutrient application influences regulated CAFOs in two major ways: 1) the dairy operators are forced to recognize nutrients inherent to the soil in their fertilizer and manure management decisions and 2) they must dispose off-farm of manure produced by the farm animals in excess of the soils' capacity to receive manure nutrients. Effects that the land nutrient restrictions and the costs of off-site disposal of manure have on land economic values are thus an important consideration for the dairy producing region. To investigate the land value effects, we set up a stylized version of the optimization model that includes only those elements of the non-linear programming model that have direct bearing on the shadow prices of land. The presentation of the stylized nonlinear programming model and mathematical treatment of the first order conditions to derive land shadow prices follow.

<u>Model notation and variables definition</u>

Parameters:

P_W = Price per cwt of milk

P_C = Price per ton to sell corn

P_A = Price per ton to sell alfalfa

C_{Xj} = Total variable cost for raising cows, except cost of feed for cow on ration *j*

C_F = Cost per ton of feed ingredient, other than corn and alfalfa hay

C_N = Cost per unit (lb) of fertilizer N purchased

C_P = Cost per unit (lb) of fertilizer P purchased

C_{Ci} = Production cost per acre of corn on soil *i*, except fertilizers

C_{Ai} = Production cost per acre of alfalfa on soil *i*, except fertilizers

C_{SM} = Cost per ton to spread manure on fields

C_{DM} = Cost per ton to dispose of manure off-site

$\tilde{C}_C$ = Cost per ton of purchased corn

$\tilde{C}_A$ = Cost per ton of purchased alfalfa

Y_{Xj} = Milk production for cow on ration *j*, in cwt

Y_{Ci} = Tons of corn produced per acre of land *i* in corn

Y_{Ai} = Tons of alfalfa produced per acre of land *i* in alfalfa

a_{Cj} = Tons of corn used for ration *j*

a_{Aj} = Tons of alfalfa used for ration *j*

a_{Fj} = Tons of other feed used for ration *j*

M_j = Tons of manure from cow fed ration *j*

N_j = Pounds of N in manure from cow fed ration *j*

P_j = Pounds of P in manure from cow fed ration *j*

η_{Ci} = Pounds of N required per acre for corn on land *i*

η_{Ai} = Pounds of N required per acre for alfalfa on land *i*

ρ_{Ci} = Pounds of P required per acre for corn on land *i*

ρ_{Ai} = Pounds of P required per acre for alfalfa on land *i*

Variables:

X_j = Number of cows on ration *j*

F = Tons of other feed purchased

BN_{Ci} = Pounds of N purchased for corn on land *i*

BN_{Ai} = Pounds of N purchased for alfalfa on land *i*

BP_{Ci} = Pounds of N purchased for corn on land *i*

BP_{Ai} = Pounds of N purchased for alfalfa on land *i*

A_{Ci} = Acres of land *i* in corn

A_{Ai} = Acres of land *i* in alfalfa

SM_{Ci} = Tons of manure spread on corn on land *i*

SM_{Ai} = Tons of manure spread on alfalfa on land *i*

S_C = Tons of corn sold

S_A = Tons of alfalfa sold

B_C = Tons of corn purchased

B_A = Tons of alfalfa purchased

M = Total tons of manure produced

DM = Tons of manure disposed off-site

N_M = Total pounds of N in manure produced

P_M = Total pounds of P in manure produced

<u>The optimization problem</u>

$$Max\Big[\ \sum_{j=1}^{2}\left(P_W Y_{Xj} - C_{Xj}\right)X_{j} - C_F F - C_N \left[\sum_{i=1}^{3} BN_{Ci} + \sum_{i=1}^{3} BN_{Ai}\right]$$

$$- C_P \left[\sum_{i=1}^{3} BP_{Ci} + \sum_{i=1}^{3} BP_{Ai}\right] - \sum_{i=1}^{3} C_{Ci} A_{Ci} - \sum_{i=1}^{3} C_{Ai} A_{Ai}$$

$$- C_{SM} \left[\sum_{i=1}^{3} SM_{Ci} - \sum_{i=1}^{3} SM_{Ai}\right] - C_{DM} DM + P_C S_C + P_A S_A$$

$$- \tilde{C}_C B_C - \tilde{C}_A B_A \ \Big]$$

$$\begin{pmatrix} Xj, F, BN_{Ci}, BN_{Ai}, BP_{Ci}, BP_{Ai}, A_{Ci}, A_{Ai}, SM_{Ci}, SM_{Ai}, DM, \\ S_C, S_A, B_C, B_A, M, N_M, P_M \end{pmatrix} \geq 0$$

$j = 1, 2$ (I.1)

such that:

Corn grain in ration, production, selling, and buying:

$$a_{C1} X_1 + a_{C2} X_2 - \sum_{i=1}^{3} Y_{Ci} A_{Ci} + S_C - B_C \leq 0 \qquad \text{(I.2)}$$

Alfalfa in ration, production, selling, and buying:

$$a_{A1} X_1 + a_{A2} X_2 - \sum_{i=1}^{3} Y_{Ai} A_{Ai} + S_A - B_A \leq 0 \qquad \text{(I.3)}$$

Other feeds in ration, and buying:

$$a_{F1} X_1 + a_{F2} X_2 - F \leq 0 \qquad \text{(I.4)}$$

Manure production:

$$- M_1 X_1 - M_2 X_2 + M \leq 0 \qquad \text{(I.5)}$$

N and P production in manure:

$$- N_1 X_1 - N_2 X_2 + N_M \leq 0 \qquad \text{(I.6)}$$

$$-P_1X_1 - P_2X_2 + P_M \le 0 \qquad \text{(I.7)}$$

N and P application on corn:

$$\eta_{Ci}A_{Ci} - BN_{Ci} - \delta_N SM_{Ci} \le 0 \qquad (i = 1, 2, 3) \qquad \text{(I.8)}$$

$$\rho_{Ci}A_{Ci} - BP_{Ci} - \delta_P SM_{Ci} \le 0 \qquad (i = 1, 2, 3) \qquad \text{(I.9)}$$

N and P application on alfalfa:

$$\eta_{Ai}A_{Ai} - BN_{Ai} - \delta_N SM_{Ai} \le 0 \qquad (i = 1, 2, 3) \qquad \text{(I.10)}$$

$$\rho_{Ai}A_{Ai} - BP_{Ai} - \delta_P SM_{Ai} \le 0 \qquad (i = 1, 2, 3) \qquad \text{(I.11)}$$

Manure inventory:

$$\sum_{i=1}^{3} SM_{Ci} + \sum_{i=1}^{3} SM_{Ai} + DM - M \le 0 \qquad \text{(I.12)}$$

Land:

$$A_{Ai} + A_{Ai} \le L_i \qquad (i = 1, 2, 3) \qquad \text{(I.13)}$$

Dairy cow inventory:

$$X_1 + X_2 \le H \qquad \text{(I.14)}$$

where:

$$\delta_N = N_m / M$$

$$\delta_P = N_P / M$$

The Lagrangian

$$L = \Big[\ \sum_{j=1}^{2}\left(P_W Y_{Xj} - C_{Xj}\right)X_j - C_F F - C_N\left[\sum_{i=1}^{3} BN_{Ci} + \sum_{i=1}^{3} BN_{Ai}\right]$$

$$- C_P\left[\sum_{i=1}^{3} BP_{Ci} + \sum_{i=1}^{3} BP_{Ai}\right] - \sum_{i=1}^{3} C_{Ci}A_{Ci} - \sum_{i=1}^{3} C_{Ai}A_{Ai}$$

$$- C_{SM}\left[\sum_{i=1}^{3} SM_{Ci} - \sum_{i=1}^{3} SM_{Ai}\right] - C_{DM}DM + P_C S_C + P_A S_A$$

$$- \tilde{C}_C B_C - \tilde{C}_A B_A\ \Big] + \lambda_C\left[0 - \left(a_{C1}X_1 + a_{C2}X_2 - \sum_{i=1}^{3} Y_{Ci}A_{Ci} + S_C - B_C\right)\right]$$

$$+ \lambda_A\left[0 - \left(a_{A1}X_1 + a_{A2}X_2 - \sum_{i=1}^{3} Y_{Ai}A_{Ai} + S_A - B_A\right)\right] + \lambda_F\left[F - \left(a_{F1}X_1 + a_{F2}X_2\right)\right]$$

$$+ \lambda_M\left[0 - \left(-M_1X_1 - M_2X_2 + M\right)\right] + \lambda_{NM}\left[0 - \left(-N_1X_1 - N_2X_2 + N_M\right)\right]$$

$$+ \lambda_{PM}\left[0 - \left(-P_1X_1 - P_2X_2 + P_M\right)\right] + \lambda_{NCi}\left[0 - \left(\eta_{Ci}A_{Ci} - BN_{Ci} - \delta_N \cdot SM_{Ci}\right)\right]$$

$$+\lambda_{PCi}\left[0-\left(\rho_{Ci}A_{Ci}-BP_{Ci}-\delta_P\cdot SM_{Ci}\right)\right]+\lambda_{NAi}\left[0-\left(\eta_{Ai}A_{Ai}-BN_{Ai}-\delta_N\cdot SM_{Ai}\right)\right]$$
$$+\lambda_{PAi}\left[0-\left(\rho_{Ai}A_{Ai}-BP_{Ai}-\delta_P\cdot SM_{Ai}\right)\right]$$
$$+\lambda_{MSD}\left[0-\left(\sum_{i=1}^{3}SM_{Ci}+\sum_{i=1}^{3}SM_{Ai}+DM-M\right)\right]+\lambda_{Li}\left[L_i-\left(A_{Ai}+A_{Ai}\right)\right]$$
$$+\lambda_H\left[H-\left(X_1+X_2\right)\right] \tag{I.15}$$

where:

$\delta_N = N_m/M$; $\delta_P = N_P/M$

General representation of the (Kuhn-Tucker) first-order necessary conditions[33]

$$L_\nu \le 0;\ L_\lambda \ge 0 \tag{I.16}$$

$$\nu\cdot L_\nu = 0;\ \lambda\cdot L_\lambda = 0 \tag{I.17}$$

$$\nu \ge 0;\ \lambda \ge 0 \tag{I.18}$$

where $L_\ell = \partial L/\partial \ell$ *for* $\ell = \nu,\lambda$

ν = Variable

λ = Lagrangian multiplier associated with constraint

The first order conditions I: $L_\nu \le 0$

$$L_{X1}:\left(P_W Y_{X1}-C_{X1}\right)-\lambda_C\left(a_{C1}\right)-\lambda_a\left(a_{A1}\right)-\lambda_F\left(a_{F1}\right)+\lambda_M\left(M_1\right)+\lambda_{NM}\left(N_1\right)$$
$$+\lambda_{PM}\left(P_1\right)+\lambda_H\left(-1\right)\le 0 \tag{I.19}$$

$$L_{X2}:\left(P_W Y_{X2}-C_{X2}\right)-\lambda_C\left(a_{C2}\right)-\lambda_a\left(a_{A2}\right)-\lambda_F\left(a_{F2}\right)+\lambda_M\left(M_2\right)+\lambda_{NM}\left(N_2\right)$$
$$+\lambda_{PM}\left(P_2\right)+\lambda_H\left(-1\right)\le 0 \tag{I.20}$$

$$L_F: -C_F+\lambda_F \le 0 \tag{I.21}$$

$$L_{SC}: P_{SC}-\lambda_C \le 0 \tag{I.22}$$

$$L_{SA}: P_{SA}-\lambda_A \le 0 \tag{I.23}$$

[33] H.W. Kuhn and A.W. Tucker, 1951.

$$L_{BC} : -\tilde{C}_C + \lambda_C \le 0 \tag{I.24}$$

$$L_{BA} : -\tilde{C}_A + \lambda_A \le 0 \tag{I.25}$$

$$L_M : -\lambda_M - \sum_{i=1}^{3} \lambda_{NAi} \cdot N_M \cdot M^{-2} \cdot SM_{Ai} - \sum_{i=1}^{3} \lambda_{PAi} \cdot P_M \cdot M^{-2} \cdot SM_{Ai}$$

$$- \sum_{i=1}^{3} \lambda_{NCi} \cdot N_M \cdot M^{-2} \cdot SM_{Ci} - \sum_{i=1}^{3} \lambda_{PCi} \cdot P_M \cdot M^{-2} \cdot SM_{Ci} \le 0 \tag{I.26}$$

$$L_{NM} : -\lambda_{NM} + \sum_{i=1}^{3} \lambda_{NCi} \cdot 1/M \cdot SM_{Ci} + \sum_{i=1}^{3} \lambda_{NAi} \cdot 1/M \cdot SM_{Ai} \le 0 \tag{I.27}$$

$$L_{PM} : -\lambda_{PM} + \sum_{i=1}^{3} \lambda_{PCi} \cdot 1/M \cdot SM_{Ci} + \sum_{i=1}^{3} \lambda_{PAi} \cdot 1/M \cdot SM_{Ai} \le 0 \tag{I.28}$$

$$L_{BNCi} : -C_N + \lambda_{NCi} \le 0 \qquad (i = 1, 2, 3) \tag{I.29}$$

$$L_{BNAi} : -C_N + \lambda_{NAi} \le 0 \qquad (i = 1, 2, 3) \tag{I.30}$$

$$L_{BPCi} : -C_P + \lambda_{PCi} \le 0 \qquad (i = 1, 2, 3) \tag{I.31}$$

$$L_{BPAi} : -C_P + \lambda_{PAi} \le 0 \qquad (i = 1, 2, 3) \tag{I.32}$$

$$L_{ACi} : -C_{Ci} + \lambda_C Y_{Ci} - \lambda_{NCi}\eta_{Ci} - \lambda_{PCi}\rho_{Ci} - \lambda_{Li} \le 0 \qquad (i = 1, 2, 3) \tag{I.33}$$

$$L_{AAi} : -C_{Ai} + \lambda_A Y_{Ai} - \lambda_{NAi}\eta_{Ai} - \lambda_{PAi}\rho_{Ai} - \lambda_{Li} \le 0 \qquad (i = 1, 2, 3) \tag{I.34}$$

$$L_{SMCi} : -C_{SM} + \lambda_{NCi}\sigma_N + \lambda_{PCi}\sigma_P - \lambda_{MSD} \le 0 \qquad (i = 1, 2, 3) \tag{I.35}$$

$$L_{SMAi} : -C_{SM} + \lambda_{NAi}\sigma_N + \lambda_{PAi}\sigma_P - \lambda_{MSD} \le 0 \qquad (i = 1, 2, 3) \tag{I.36}$$

$$L_{DM} : -C_{DM} - \lambda_{MSD} \le 0 \tag{I.37}$$

<u>The first order conditions II</u>: $L_\lambda \ge 0$

$$L_{\lambda C} : \sum_{i=1}^{3} Y_{Ci} A_{Ci} \ge a_{C1} X_1 + a_{C2} X_2 + S_C \tag{I.38}$$

$$L_{\lambda A} : \sum_{i=1}^{3} Y_{Ai} A_{Ai} \ge a_{A1} X_1 + a_{A2} X_2 + S_A \tag{I.39}$$

$$L_{\lambda F} : F \ge a_{F1} X_1 + a_{F2} X_2 \tag{I.40}$$

$$L_{\lambda M} : M \ge M_1 X_1 + M_2 X_2 \tag{I.41}$$

$$L_{\lambda NM} : N_1 X_1 + N_2 X_2 \ge N_M \tag{I.42}$$

$$L_{\lambda PM} : P_1 X_1 + P_2 X_2 \ge P_M \tag{I.43}$$

$$L_{\lambda NCi} : \sigma_N SM_{Ci} + BN_{Ci} \ge \eta_{NCi} A_{Ci} \qquad (i=1, 2, 3) \tag{I.44}$$

$L_{\lambda NAi}: \sigma_N SM_{Ai} + BN_{Ai} \geq \eta_{NAi} A_{Ai}$ (*i*=*1*, *2*, *3*) (I.45)

$L_{\lambda PCi}: \sigma_P SM_{Ci} + BP_{Ci} \geq \eta_{PCi} A_{Ci}$ (*i*=*1*, *2*, *3*) (I.46)

$L_{\lambda PAi}: \sigma_P SM_{Ai} + BP_{Ai} \geq \eta_{PAi} A_{Ai}$ (*i*=*1*, *2*, *3*) (I.47)

$L_{\lambda MSD}: M \geq \sum_{i=1}^{3} SM_{Ci} + \sum SM_{Ai} + DM$ (I.48)

$L_{\lambda Li}: L_i \geq A_{Ci} + A_{Ai}$ (*i*=*1*, *2*, *3*) (I.49)

$L_{\lambda H}: H \geq X_1 + X_2$ (I.50)

<u>The first order conditions III (complementary slackness):</u> $\nu \cdot L_X = 0$

$\nu \geq 0$ for all ν

$$X_1 \cdot L_{X1}: X_1\left[(P_W Y_{X1} - C_{X1}) - \lambda_C (a_{C1}) - \lambda_a (a_{A1}) - \lambda_F (a_{F1}) + \lambda_M (M_1) \right.$$
$$\left. + \lambda_{NM}(N_1) + \lambda_{PM}(P_1) - \lambda_H \right] = 0 \quad \text{(I.51)}$$

$$X_2 \cdot L_{X2}: X_2\left[(P_W Y_{X2} - C_{X2}) - \lambda_C (a_{C2}) - \lambda_a (a_{A2}) - \lambda_F (a_{F2}) + \lambda_M (M_2) \right.$$
$$\left. + \lambda_{NM}(N_2) + \lambda_{PM}(P_2) - \lambda_H \right] = 0 \quad \text{(I.52)}$$

$F \cdot L_F : F[-C_F + \lambda_F] = 0$ (I.53)

$S_C \cdot L_{SC} : S_C[P_{SC} - \lambda_C] = 0$ (I.54)

$S_A \cdot L_{SA} : S_A[P_{SA} - \lambda_A] = 0$ (I.55)

$B_C \cdot L_{BC} : B_C\left[-\tilde{C}_C + \lambda_C\right] = 0$ (I.56)

$B_A \cdot L_{BA} : B_A\left[-\tilde{C}_A + \lambda_A\right] = 0$ (I.57)

$$M \cdot L_M : M\left[-\lambda_{MSD} - \sum_{i=1}^{3} \lambda_{NAi} \cdot N_M \cdot M^{-2} \cdot SM_{Ai} - \sum_{i=1}^{3} \lambda_{PAi} \cdot P_M \cdot M^{-2} \cdot SM_{Ai} \right.$$
$$\left. - \sum_{i=1}^{3} \lambda_{NCi} \cdot N_M \cdot M^{-2} \cdot SM_{Ci} - \sum_{i=1}^{3} \lambda_{PCi} \cdot P_M \cdot M^{-2} \cdot SM_{Ci} \right] = 0 \quad \text{(I.58)}$$

$$N_M \cdot L_{NM} : N_M\left[-\lambda_{NM} + \sum_{i=1}^{3} \lambda_{NCi} \cdot 1/M \cdot SM_{Ci} + \sum_{i=1}^{3} \lambda_{NAi} \cdot 1/M \cdot SM_{Ai} \right] = 0$$

(I.59)

$$P_M \cdot L_{PM} : P_M\left[-\lambda_{PM} + \sum_{i=1}^{3} \lambda_{PCi} \cdot 1/M \cdot SM_{Ci} + \sum_{i=1}^{3} \lambda_{PAi} \cdot 1/M \cdot SM_{Ai} \right] = 0$$

(I.60)

$BN_{Ci} \cdot L_{BNCi} : BN_{Ci}[-C_N + \lambda_{NCi}] = 0$ (*i* = *1*, *2*, *3*) (I.61)

$$BN_{Ai} \cdot L_{BNAi} : BN_{Ai}\left[-C_N + \lambda_{NAi}\right] = 0 \qquad (i = 1, 2, 3) \qquad \text{(I.62)}$$

$$BP_{Ci} \cdot L_{BPCi} : BP_{Ci}\left[-C_P + \lambda_{PCi}\right] = 0 \qquad (i = 1, 2, 3) \qquad \text{(I.63)}$$

$$BP_{Ai} \cdot L_{BPAi} : BP_{Ai}\left[-C_P + \lambda_{PAi}\right] = 0 \qquad (i = 1, 2, 3) \qquad \text{(I.64)}$$

$$A_{Ci} \cdot L_{ACi} : A_{Ci}\left[\lambda_C Y_{Ci} - C_{Ci} - \lambda_{NCi}\eta_{Ci} - \lambda_{PCi}\rho_{Ci} - \lambda_{Li}\right] = 0 \qquad (i = 1, 2, 3) \qquad \text{(I.65)}$$

$$A_{Ai} \cdot L_{AAi} : A_{Ai}\left[\lambda_A Y_{Ai} - C_{Ai} - \lambda_{NAi}\eta_{Ai} - \lambda_{PAi}\rho_{Ai} - \lambda_{Li}\right] = 0 \qquad (i = 1, 2, 3) \qquad \text{(I.66)}$$

$$SM_{Ci} \cdot L_{SMCi} : SM_{Ci}\left[-C_{SM} + \lambda_{NCi}\sigma_N + \lambda_{PCi}\sigma_P - \lambda_{MSD}\right] = 0 \qquad (i = 1, 2, 3) \qquad \text{(I.67)}$$

$$SM_{Ai} \cdot L_{SMAi} : SM_{Ai}\left[-C_{SM} + \lambda_{NAi}\sigma_N + \lambda_{PAi}\sigma_P - \lambda_{MSD}\right] = 0 \qquad (i = 1, 2, 3) \qquad \text{(I.68)}$$

$$DM \cdot L_{DM} : DM\left[-C_{DM} - \lambda_{MSD}\right] = 0 \qquad \text{(I.69)}$$

<u>The first order conditions IV (complementary slackness):</u> $\lambda \cdot L_\lambda = 0$

$\lambda \geq 0$ for all λ

$$\lambda_C \cdot L_{\lambda C} : \lambda_C\left[\sum_{i=1}^{3} Y_{Ci}A_{Ci} - a_{C1}X_1 - a_{C2}X_2 - S_C + B_C\right] \qquad \text{(I.70)}$$

$$\lambda_A \cdot L_{\lambda A} : \lambda_A\left[\sum_{i=1}^{3} Y_{Ai}A_{Ai} - a_{A1}X_1 - a_{A2}X_2 - S_A + B_A\right] \qquad \text{(I.71)}$$

$$\lambda_F \cdot L_{\lambda F} : \lambda_F\left[F - a_{F1}X_1 - a_{F2}X_2\right] \qquad \text{(I.72)}$$

$$\lambda_M \cdot L_{\lambda M} : \left[M_1X_1 + M_2X_2 - M\right] \qquad \text{(I.73)}$$

$$\lambda_{NM} \cdot L_{\lambda NM} : \lambda_{NM}\left[N_1X_1 + N_2X_2 - N_M\right] \qquad \text{(I.74)}$$

$$\lambda_{PM} \cdot L_{\lambda PM} : \lambda_{PM}\left[P_1X_1 + P_2X_2 - P_M\right] \qquad \text{(I.75)}$$

$$\lambda_{NCi} \cdot L_{\lambda NCi} : \lambda_{NCi}\left[\delta_N \cdot SM_{Ci} + BN_{Ci} - \eta_{Ci}A_{Ci}\right] \qquad \text{(I.76)}$$

$$\lambda_{NAi} \cdot L_{\lambda NAi} : \lambda_{NAi}\left[\delta_N \cdot SM_{Ai} + BN_{Ai} - \eta_{Ai}A_{Ai}\right] \qquad \text{(I.77)}$$

$$\lambda_{PCi} \cdot L_{\lambda PCi} : \lambda_{PCi}\left[\delta_P \cdot SM_{Ci} + BP_{Ci} - \rho_{Ci}A_{Ci}\right] \qquad \text{(I.78)}$$

$$\lambda_{PAi} \cdot L_{\lambda PAi} : \lambda_{PAi}\left[\delta_P \cdot SM_{Ai} + BP_{Ai} - \rho_{Ai}A_{Ai}\right] \qquad \text{(I.79)}$$

$$\lambda_{MSD} \cdot L_{\lambda MSD} : \lambda_{MSD}\left[0 - \left(\sum_{i=1}^{3} SM_{Ci} + \sum_{i=1}^{3} SM_{Ai} + DM - M\right)\right] + \lambda_{Li}\left[L_i - \left(A_{Ai} + A_{Ai}\right)\right] \qquad \text{(I.80)}$$

$$\lambda_H \cdot L_{\lambda H} : \lambda_H\left[H - X_1 - X_2\right] \qquad \text{(I.81)}$$

APPENDIX 2.B

ANALYSIS OF LAND SHADOW VALUE

To analyze how the new nutrient regulations for CAFOs influence the economic value of crop land, the Kuhn-Tucker necessary conditions (for an optimum solution) are examined in detail. In general, crop production and nutrient management activities on corn and alfalfa drive land internal values. The case is examined (without loss in generality) for land in crop production. A similar treatment of the first order conditions can be done for alfalfa. Kuhn-Tucker necessary conditions from the previous section (appendix) relevant to the analysis of land shadow prices are restated:

$$L_{ACi} : -C_{Ci} + \lambda_C Y_{Ci} - \lambda_{NCi}\eta_{Ci} - \lambda_{PCi}\rho_{Ci} - \lambda_{Li} \leq 0 \qquad (i = 1, 2, 3) \qquad \text{(II.1)}$$

$$L_{SMCi} : -C_{SM} + \lambda_{NCi}\sigma_N + \lambda_{PCi}\sigma_P - \lambda_{MSD} \leq 0 \qquad (i = 1, 2, 3) \qquad \text{(II.2)}$$

$$L_{BPCi} : -C_P + \lambda_{PCi} \leq 0 \qquad (i = 1, 2, 3) \qquad \text{(II.3)}$$

$$L_{BNCi} : -C_N + \lambda_{NCi} \leq 0 \qquad (i = 1, 2, 3) \qquad \text{(II.4)}$$

$$L_{DM} : -C_{DM} - \lambda_{MSD} \leq 0 \qquad \text{(II.5)}$$

where equations (II.1) through (II.4) are first-order equations associated with crop production and manure and fertilizer N application on corn, for three classes of soils based on soil P test values. The shadow price for land appears as a variable in equation (II.1) while equation (II.2) considers manure spreading on corn. Equations (II.3) and (II.4) account for the shadow values of P and N applied on corn. Equation (II.5) is a necessary condition determining the economic cost of off-farm manure disposal for the dairy CAFOs. To see how the land shadow prices are affected by the nutrient restrictions we must rearrange the equations and make some assumptions about the nature of the optimal solutions.

Re-arranging equation (II.1) gives:

$$\lambda_{Li} \geq \lambda_C Y_{Ci} - C_{Ci} - \lambda_{NCi}\eta_{Ci} - \lambda_{PCi}\rho_{Ci} \qquad (i = 1, 2, 3) \qquad \text{(II.6)}$$

where λ_{Li}, λ_C, Y_{Ci}, C_{Ci}, λ_{NCi}, η_{Ci}, λ_{PCi} and ρ_{Ci} are as defined in appendix 2.I. Corn is grown on land *i* (for *i= 1, 2, 3*). For positive value of the acreage of land *i* in corn, i.e., A_{Ci}, equation (II.6) holds with equality by the first-order necessary conditions for an optimal solution (see equation I.65 in appendix 2.I).

The manure spreading expression (i.e. equation II.2) is re-arranged so that:

$$\lambda_{NCi}\sigma_N + \lambda_{PCi}\sigma_P \leq C_{SM} + \lambda_{MSD} \qquad (i = 1, 2, 3) \qquad \text{(II.7)}$$

where the terms in equation (7) are as defined in the appendix (2.I). For SM_{Ci} that is strictly positive (*i = 1,2,3*), i.e., when manure is spread on corn on land *i*, the necessary conditions in the equation hold with equality (see equation I.67).

Our analysis of land shadow value focuses on the relative values of the high and low soil P land classifications. For convenience however, we include equations for the medium soil test P category.

General Assumptions

The relevant expressions of the Kuhn-Tucker conditions can be set up for the base (no-policy) and nutrients restrictions policy scenarios. In both cases, we assume that corn is grown on the land soil test P (STP) classes so that equation (II.6) holds with equality. Further, the stylized examples do not account for land types due to differences in soil capabilities (i.e. corn yield) so that Y_{Ci}, the corn yield per acre is constant for all *i* (i.e., $Y_{Ci} = Y_C$ for *i=1, 2, 3*). Similarly, the costs of crop production are assumed uniform for corn land of all soil test types in the base and policy scenarios, (i.e., $C_{Ci} = C_C$ for *i=1, 2, 3*).

Base Case:

In the model simulation with no restrictions on nutrient applications, over-application of manure nutrients is allowed and manure is spread on all the soil test types (i.e., equation II.7 holds with equality). Supplemental fertilizer applications are further determined by the crop nutrient uptake levels and do not account for nutrients inherent in soil. Since the nutrient applications do not account for soil inherent nutrients, the terms representing nitrogen requirements on low, medium and high STP soils in the first order equations are assumed equivalent (i.e., $\eta_{Ci} = \eta_C$ for *i=1, 2, 3*). Phosphorus requirements are similarly assumed equivalent for the soil test types (i.e., $\rho_{Ci} = \rho_C$ for *i=1, 2, 3*).

Assume that *i* represents high, medium and low soil test P land, respectively (for *i = 1, 2, and 3*), then for the general assumptions stated in the section above and in the no- policy case, equation (II.6) can be re-written for corn land as[34]:

$$\lambda_{L1} = \lambda_C Y_C - C_C - \lambda_{NC}\eta_C - \lambda_{PC}\rho_C \quad \text{(II.8)}$$

$$\lambda_{L2} = \lambda_C Y_C - C_C - \lambda_{NC}\eta_C - \lambda_{PC}\rho_C \quad \text{(II.9)}$$

$$\lambda_{L3} = \lambda_C Y_C - C_C - \lambda_{NC}\eta_C - \lambda_{PC}\rho_C \quad \text{(II.10)}$$

where λ_{L1}, λ_{L2} and λ_{L3} are the shadow prices of land on high, medium and low soil test P land, respectively.

By equations (II.8) through (II.10), the following holds:

[34] By equations (II.4) and (II.5) and the equality assumption on Equation (II.6) for all soil P types, $\lambda_{NC1} = \lambda_{NC2} = \lambda_{NC3} = \lambda_{NC}$ and $\lambda_{PC1} = \lambda_{PC2} = \lambda_{PC3} = \lambda_{PC}$ hold in the no-policy scenario.

$$\lambda_{L1} = \lambda_{L2} = \lambda_{L3} \tag{II.11}$$

Clearly, land internal values are equivalent for the soil test P classifications in the base scenario.

Nutrients Restrictions Policy and Manure Disposal Costs

Under the new nutrient standards, manure and fertilizer nutrients are applied on farm land only up to the P and N requirements of the crop-soil combinations. Manure over-application is not allowed so that manure is not spread on the high P land (i.e., equation (II.7) holds with equality for the medium and low soil P classes only). Further, nutrient requirement levels are set at the agronomic uptake levels of the crops and account for the soil inherent nutrient (i.e., soil test P status). As in the base case and to restrict the analysis to the direct effects of policy on the values of the variable P-status land, the crop nitrogen requirements are assumed equivalent on high, medium and low STP soils (i.e., $\eta_{Ci} = \eta_C$ for $i=1,2,3$). No manure or fertilizer P is applied on high P soils. Consequently, ρ_{Ci} in equation (II.6) is set equal to zero for the high soil P class.

The phosphorus requirement on land designated medium STP is by definition a fraction of the P requirement on low STP soils. This is represented as:

$$\rho_{C2} = \gamma_C \rho_{C3} \qquad 0 < \gamma_C < 1 \tag{II.12}$$

where ρ_{C2} and ρ_{C3} denote P nutrient requirements for corn on medium and low STP soils, respectively, and ρ_{C3} is a higher value than ρ_{C2} by definition.

Given the general assumptions in the earlier section and the stylized assumptions under the policy scenario, equation (II.6) can be re-written for the policy scenario as:

$$\lambda_{L1} = \lambda_C Y_C - C_C - \lambda_{NC1}\eta_C \tag{II.13}$$

$$\lambda_{L2} = \lambda_C Y_C - C_C - \lambda_{NC2}\eta_C - \lambda_{PC2}\gamma_C \rho_{C3} \tag{II.14}$$

$$\lambda_{L3} = \lambda_C Y_C - C_C - \lambda_{NC3}\eta_C - \lambda_{PC3}\rho_{C3} \tag{II.15}$$

where λ_{L1}, λ_{L2} and λ_{L3} are the shadow prices of land on high, medium and low soil test P land, respectively. We can say something about the (magnitude) order of the land shadow values under the policy scenario for additional information on λ_{NCi} and λ_{PCi} for all *i*.

For the simple case where λ_{NCi} is equivalent to λ_{NC} for all *i* and λ_{PCi} equals λ_{PC} for all *i* (as in the base case), the following relationship holds:

$$\lambda_{L1} > \lambda_{L2} > \lambda_{L3} \tag{II.16}$$

where λ_{L1}, λ_{L2} and λ_{L3} are as defined earlier and equation (II.16) denotes that high P land has an internal value higher than that of the medium P land. In turn, the shadow price of the medium P land is greater than that of the low P land. Equation (II.16) holds given the relationship between soil P requirements on medium and low P land (i.e., equation (II.12)) and the assumption that P requirements on these land types are strictly positive (i.e., $\rho_{C2} > 0$ and $\rho_{C3} > 0$).

Next, we examine the relative magnitudes of the land shadow values when λ_{NCi} and λ_{PCi} are not equivalent for all *i*. In particular, we examine relevant Kuhn-Tucker (first-order optimality) conditions to show that for a stylized set of solutions for the nutrient policy scenario, it holds that the land internal value is greater for the high P soils (than on low P soils) for some range of manure disposal costs while it is lower for an alternative set of off-site manure disposal costs.

Switch in the Order (Magnitude) of Land Shadow Values

For a stylized case of the new nutrients policy, we assume that fertilizer P is purchased as supplement for manure P on the medium and low P soils[35]. The implication of this assumption for the Kuhn-Tucker (first-order) conditions is that equation (II.3) holds with equality for the land with medium and low P soils[36]. Further, manure application on the medium and low P soils (and not on the high P land) allows for equation (II.3) to be re-written for land of soil test type *i* (for *i=1, 2, 3*) as:

$$\lambda_{NC1} \leq \left[C_{SM} + \lambda_{MSD} - \lambda_{PC1}\sigma_P\right]\cdot 1/\sigma_N \tag{II.17}$$

$$\lambda_{NC2} = \left[C_{SM} + \lambda_{MSD} - \lambda_{PC2}\sigma_P\right]\cdot 1/\sigma_N \tag{II.18}$$

$$\lambda_{NC3} = \left[C_{SM} + \lambda_{MSD} - \lambda_{PC3}\sigma_P\right]\cdot 1/\sigma_N \tag{II.19}$$

where λ_{NC1}, λ_{NC2} and λ_{NC3} denote the value of N applied on high, medium and low P land, respectively.

Substitute the expressions in equations (II.18) and (II.19) into the land value equations in (II.14) and (II.15) and recall the equality assumption on equation (II.3) so that the value of P on corn is equivalent on medium and low P soils. Further, assume the case in which excess manure is shipped from the CAFOs to off-site recipients and

[35] This solution is consistent with our modeling solutions of the parametric analysis of (the implications of) manure disposal costs for CAFOs in the selected three-county dairy industry.

[36] A further implication is that $\lambda_{PC2} = \lambda_{PC3} = \lambda_{PC}$ holds.

substitute the (negative of) C_{DM}, the cost of off-site manure disposal for the shadow price on manure disposal (λ_{MSD}), as in equation (5).

Equations (II.13) through (II.15) can now be re-written as:

$$\lambda_{L1} = \lambda_C Y_C - C_C - \lambda_{NC1}\eta_C \quad \text{(II.20)}$$

$$\lambda_{L2} = \lambda_C Y_C - C_C - \left[C_{SM} - C_{DM} - \lambda_{PC}\sigma_P\right]\cdot 1/\sigma_N \cdot \eta_C - \lambda_{PC}\gamma_C\rho_{C3} \quad \text{(II.21)}$$

$$\lambda_{L3} = \lambda_C Y_C - C_C - \left[C_{SM} - C_{DM} - \lambda_{PC}\sigma_P\right]\cdot 1/\sigma_N \cdot \eta_C - \lambda_{PC}\rho_{C3} \quad \text{(II.22)}$$

where the sign on the off-site manure disposal cost variable, (i.e., C_{DM}, in equations II.21 and II.22) indicates that the land shadow values on medium and low P land increase as the unit cost of off-site manure disposal rises. The size of the manure disposal cost relative to the cost of spreading manure (C_{SM}) is also important.

Assume a low cost for off-site manure disposal (C_{DM}) so that the relevant expression in equations (21) and (22) is zero or negative (i.e., $-\left[C_{SM} - C_{DM} - \lambda_{PC}\sigma_P\right] \leq 0$). This holds (for e.g.) when the unit cost of spreading manure on farmland exceeds the off-site manure disposal cost. Then by equations (II.20) and (II.22) and recalling ($\lambda_{NC1} \leq \left[C_{SM} + \lambda_{MSD} - \lambda_{PC1}\sigma_P\right]\cdot 1/\sigma_N$), it holds that:

$$\lambda_{L1} > \lambda_{L3} \quad \text{(II.23)}$$

where the expression in equation (II.23) denotes higher shadow price for land of high soil P category (i.e., λ_{L1}). This is the case because a higher (positive) sum is subtracted from λ_{L3} (i.e., from $\lambda_C Y_C - C_C$ in equation (II.22)) than from λ_{L1} (i.e., from $\lambda_C Y_C - C_C$ in equation (II.20)).

Next, assume alternative costs of off-site manure disposal so that the value of C_{DM} rises in the equations and the relevant expression in equations (II.21) and (II.22) is positive (i.e., $-\left[C_{SM} - C_{DM} - \lambda_{PC}\sigma_{P}\right] \geq 0$). Note that while this (now) positive term increases the overall value of λ_{Li} for all soil test types (i.e., for *i=1, 2, 3*), the negative values on the last terms (on the right hand side) in equations (II.21) and (II.22) dampen the positive effects on the land shadow value.

However, a large enough increase in C_{DM}, the cost of off-farm manure disposal would counter the otherwise negative effect on land values so that the following holds for high and low soil P land:

$$\lambda_{L1} < \lambda_{L3} \tag{II.24}$$

where equation (II.24) shows higher shadow price for land of low soil P category (λ_{L3}).

Thus, we have shown for a stylized policy scenario that land internal values switch in magnitude order for alternative costs for off-site manure disposal. More formally, we present in (Table A.2.) the relevant cases determining the relative shadow values of medium and low P soils for our stylized policy scenario and the critical values at which the reversal in shadow land values occur.

Explaining the Switch in Land Economic Value

When no policy is in effect, the CAFO farm nutrient management does not account for the inherent value of soil nutrients. Consequently, and for constant soil yield capabilities, the shadow prices are uniform for the soil test P categories of land. With the new nutrient policy in effect, however, farm nutrient management and the land internal value recognize crop land as a repository of soil nutrients. This intrinsic value is obvious in (higher) shadow prices on high soil test P lands when the unit cost of off-farm manure disposal is very low.

However, as it costs more to dispose (off-farm) of the manure nutrients produced in excess of the farm crop agronomic needs, land takes on additional value as manure disposal sites. This economic value of the land accounts for the opportunity cost of not putting the land to use as a manure-receiving site. Lower P soils that can receive additional manure thus increase in economic value relative to the high P soils that would have been more attractive purely from a soil nutrient availability perspective.

Table A.2: Relative magnitude on land shadow values given net manure disposal costs relative to spreading and the value of manure N on corn land

(CDM-CSM)$^{+}$	$\lambda_{NC}\sigma_N < (CDM - CSM)$	$\lambda_{NC}\sigma_N \geq (CDM - CSM)$
(CDM - CSM) < 0	$\lambda_{L3} < \lambda_{L2}$	$\lambda_{L3} \geq \lambda_{L2}$
(CDM - CSM) = 0	$\lambda_{L3} > \lambda_{L2}$	$\lambda_{L3} > \lambda_{L2}$
(CDM - CSM) > 0	$\lambda_{L3} > \lambda_{L2}$	$\lambda_{L3} > \lambda_{L2}$

$^{+}$ C_{DM} is unit cost of off-site manure disposal; C_{SM} is the unit cost of spreading manure on-farm. The difference ($C_{DM} - C_{SM}$) is the net manure disposal cost. $\lambda_{NC}\sigma_N$ is the value of manure nitrogen on land; λ_{L3} and λ_{L3} are the internal value of land on low and medium soil test P land, respectively.

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CHAPTER 3

RESOURCE-BASED SUSTAINABLE DEVELOPMENT:

AN ENERGY PLANNING MODEL FOR NIGERIA[1]

Summary

As in many countries with rapidly growing economies, energy demand in Nigeria has grown at rates that far outpace expansion in the energy industry. In particular, severe shortfall in electricity supply in the country has been identified as a major constraint to firm and household production. The national government of Nigeria, in response to the identified need, has prioritized investment in energy utilities to expand capacity for electrical power generation and distribution. Being a major oil-producing and oil-dependent economy, it is expected that much of the planned expansion in the energy industry in Nigeria would be financed by rents from the petroleum sector. However, the country's government also aspires to use revenue from oil rents to more directly fund social and economic development. Further, the government goals for energy expansion and socio-economic development must account for the objectives and activities of other major stakeholders in the economy, and growing threats to the natural resource-base indicate the need to address environmental concerns associated with the various development activities.

In this chapter, we present a model for economic development in Nigeria that characterizes the interdependent intertemporal optimization behavior of major players in the economy—the government, private sector (households and firms), public utilities and foreign oil companies. The model, which is based on established results from the literatures on the optimal exploration for and extraction of exhaustible

[1] Enahoro, D, with assistance from K.P. Donaghy and C.R. Wymer. In Preparation

resources, is employed in a deterministic simulation exercise that takes the form of a dynamic policy game.

Introduction

Nigeria aspires to use revenue from its rents from natural resource extraction, particularly of petroleum resources, to fund social and economic development. The government goals for economic empowerment include the development of material and human capacity so as to enhance sustainability and reduce the current heavy dependence of the economy on a single nonrenewable resource with highly volatile output prices. The government of Nigeria has also identified meeting the Millennium Development Goals (MDGs) of the United Nations as an important component of its long-term agenda for growth.[2] To achieve the outlined goals, urgent attention must be paid to sectors of the economy with potential for the most significant impacts. The energy sector has been identified as one of these sectors. (See e.g., World Bank, 2002.) With its growing challenges to meet fast-growing household and industry demand for electricity in the country, this sector has been touted as playing a critical role in Nigeria's economic outcome. Energy planning in general and electricity development in particular, thus, are an important consideration in any discussion on economic development planning in Nigeria.

Various useful tools have been developed for short- and medium- to long-term macroeconomic modeling and planning in Nigeria. In light of recent significant changes in the economy and of new developments in the theory and methods of macroeconomic planning and modeling, however, there may be a need for updating of the old planning tools. New methods that we develop for macroeconomic planning

[2] The MDGs can be viewed online at http://www.un.org/millenniumgoals/.

account explicitly for the oil sector as an important player in the economy, tracking the implications of sector-wide changes in this industry on other sectors. The methods also account for the increased focus of the government on such objectives as human capital development, the expansion of a nonoil sector with export potential and increased access to energy for residential and industrial consumers.

In this chapter, we attempt to integrate elements from the microeconomic, open-economy macroeconomic and natural-resource economics literatures into a useful tool for planning in a particular economic environment. We present a stylized optimization model for the energy sector in Nigeria that incorporates important government objectives for social and economic development with more traditional energy-sector planning goals of resource allocation and cost minimization of a public utility. By characterizing activities in the real economy as resulting from intertemporal optimization decisions of representative agents, our model is founded on microeconomic theory and is much in the spirit of macrodynamic models outlined in Turnovsky (2000). Further, we incorporate the strands of sector economic activities in a simulation experiment that takes the form of a dynamic game between the relevant agents. We set out to demonstrate how such a tool may be developed in theory and application. To the best of our knowledge, no such approach has been applied to resource planning and economic development in Nigeria.

The model that we develop is intended for use in determining optimal combinations of energy development programs that the national government could pursue and potential outcomes of activities in government and the private sector. In particular, the model could be used to answer such questions as how changes in government capital expenditures on public utilities and in non-oil sector development would influence productivity in the manufacturing sector. To do this, the estimated model could be employed in simulation exercises of a variety of policy scenarios.

While the results obtained from simulation exercises may not immediately lend themselves to application by policy makers, they should provide useful information for the further development of a tool with greater application potential. What the current planning model can provide is a sense of the types of policy plans that would be required to implement a comprehensive and integrated national plan for Nigeria's energy sector.

In the next section, we provide a summary of the current state of the energy sector and planning in Nigeria. Next, we briefly discuss the literature relevant to this study. We then present in some detail our model characterizing the intertemporal optimizing behaviors of relevant economic agents – the government, private sector (households and firms), multi-national oil companies, and a public sector electricity utility. Next, we present the methodology of the model estimation and our application of the model to the empirical setting, outlining the data. We also describe a forecasting and simulation exercise that we perform to determine the implications of important policy and agent decision variables. Finally, we present conclusions that can be drawn from this study.

Energy Sector and Planning in Nigeria

Many concerns have been raised regarding the capacity of the energy sector in Nigeria to support a fast-growing economy.[3] These concerns are however not peculiar to the country as they echo reports of similar challenges faced by fast-developing economies such as China, India and South Africa. In general, growth in the energy sector has not kept pace with the rising energy demand that has followed industrialization in these countries. For example, whilst the annual GDP growth rate in China was more than six times that recorded in the United States in 2007, per capita

[3] E.g., various local and international media reports and a World Bank (2002) report.

energy consumption in China was less than 20 percent that of the United States in the same year. Similarly, electricity consumption in India was only 505 kilowatt hours per person in 2007 compared to more than 13,000 kilowatt hours per capita per annum in the United States in the same year. Meanwhile, GDP growth in India outstripped that of the U.S. by 4 percentage points in the reported year. Table 3.1 presents indicators of the economic and energy conditions for selected countries in 2007. In the case of Nigeria, although economic growth has been more modest than in China, India, or in South Africa, energy supply has not kept up with rising demand associated with increased economic activity. For example, access to electricity remains severely limited with only about 40 percent of the (circa 120 million) population being connected to the national electricity grid (not shown in Table). Where customers are connected to the grid, frequent blackouts are the norm (ECN, 2003). As such, many residential and commercial consumers rely on alternative sources of electrical power and energy.

Table 3.1: Economy and energy indicators for selected countries in 2007

	China	India	Nigeria	South Africa	United States
GDP annual growth rate (%)	13	9	6	5	2
GDP per capita (USD)	2,566	1,047	1,158	5,866	45,642
Energy consumption per capita (million btu)	59	17	7	111	337
Electricity consumption per capita (kWh)	2,150	505	134	4,447	13,023
CO_2 emissions per capita (metric tons)	4.74	1.23	0.72	9.59	19.93
CO_2 emissions per GDP (metric tons/’000 GDP)	2.20	2.44	5.39	2.16	1.53

Source: Authors' calculations based on World Bank and EIA data

Reports from recent surveys indicate that urban industries in Nigeria need to make up about 70 percent of their requirements for energy (heating and electricity) using customer-sited (privately-owned) diesel and gasoline generators. The operating costs for this option are up to five times more than what would be incurred using grid electricity exclusively (Adenikinju, 2003). Further, up to 80 percent of households' cooking, heating and lighting energy needs in rural and urban households are fulfilled using wood, kerosene and other alternative fuels (ECN, 2006). The uses of these unconventional power sources could have serious economic as well as environmental implications.[4] Not unlike many other developing countries, environmental pollution in Nigeria may not seem to be a serious threat when measured using standard international measures such as total carbon dioxide (CO_2) emissions. Still, these levels could be considered high for the levels of economy output. For example, while the level of CO_2 emissions per capita in Nigeria was less than a unit metric ton in 2007, this level was more than twice (fourfold) that generated in South Africa (United States) on a national income basis (see Table 3.1).[5] However, the need for increased productivity and rapid economic development cannot be over-emphasized and improved access and supply of electrical power has been touted as critical to sustaining this industrial competitiveness and economic growth in Nigeria (see World Bank, 2002; and IMF, 2008).

One obvious objective for energy planning in Nigeria is the expansion of the capacity for grid electricity generation, transmission and distribution. Another goal is the diversification of the available energy resources. Up to 68 percent of the installed electricity generating capacity in Nigeria is in natural gas facilities while 31 percent of

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[4] Fuel wood use increases emissions of harmful air particulates while the use of alternative power generators by households and businesses increases noise and air pollution levels.
[5] Productivity limitations rather than increased levels of particulate emissions from economic activity may drive these observations.

capacity is accounted for by hydroelectricity installations. Less than 1 percent of the installed capacity is for electricity generation from oil. However, the natural gas and hydro-facilities only account for, on average, 34 and 8 percent respectively, of the total energy produced in Nigeria. On the other hand, electricity generated from oil accounts for up to 58 percent of all energy consumed (EIA, 2007). The statistics may point out a need to improve capacity utilization in gas and hydro-electric facilities, or expand the capacity and efficiency of electricity generation from oil, or both.

In an obvious response to the underutilization issues in thermal energy production, the government in its role as a petroleum industry regulator has applied policies that discourage natural gas flaring by oil-producing companies.[6] Oil companies are instead encouraged to channel more of the natural gas produced in association with crude oil extraction to public energy utilities for electricity generation. There is also increased support in public and private stakeholder circles for the development of other alternative natural resources for electricity generation. It is anticipated that much of the investment required for development projects in the energy sector would come from crude oil rents paid to the federation accounts.

The overall planning challenge for the energy sector in Nigeria can be identified as the need to integrate goals for energy sector efficiency with more economy-wide social and economic objectives.[7] Specifically, there is a need for a planning model that incorporates government targets for energy security, electricity production and consumption efficiency, and sectoral productivity growth with the objectives of businesses and households. We formulate within the framework of an intertemporal optimization model such a tool that is relevant for the Nigerian context.

[6] While activities in the petroleum sector are often led by multi-national companies, the federal government takes on partnership, regulatory and supervisory roles.
[7] Energy policy goals for Nigeria are outlined in ECN (2003). An abridged version is presented in the Appendix (3.A).

Review of the Relevant Literature

Intertemporal optimization models have been useful for analyzing economic growth and other issues of macroeconomic policy. The theory of intertemporal planning has its foundations in work done by Ramsey (1928) on the optimal rates of savings and economic growth. Assuming that the welfare of the economy can be characterized by an aggregate utility function, and making assumptions of an infinite time horizon, no technological change, constant population and constant capacities for 'enjoyment' and 'sacrifice', and independence and aggregability of 'enjoyment' and 'sacrifice' over time, Ramsey formulated the now well-known mathematical rule for investments/savings in an economy, as in equation (3.1)[8]:

$$\partial k / \partial t = f((k,t), l(t)) - c(t) = [B - (U(c) - V(l)]/u(c) \qquad (3.1)$$

where $\partial k / \partial t$ is the rate of change in capital, *k(t)*, over time, *t*; *c(t)* is defined as the total rate of consumption, and *l(t)* is the supply of labor. Income in the economy is represented by *f*, a general function of available labor and capital. *B* represents the maximum obtainable rate of utility; *U(c)* is the total rate of *utility* of consumption; *V(l)* is the total rate of *disutility* of the labor rate, *l(t)*; and *u(c)* is the change in total rate of utility as the consumption rate changes, $\partial U(c) / \partial c$. Ramsey's (1928) contributions have formed the basis for much of the later work.

Other notable contributions have since been made to the literature on optimal savings and investments in an economy (see notes to Chapter 10 in Dasgupta and Heal (1979), and Part III of Turnovsky (2000) for an overview). For example, Hotelling in

[8] In words, the rate of saving multiplied by the marginal utility of money is equal to the amount by which the total net rate of enjoyment of utility falls short of the maximum possible rate of enjoyment.

1931 applied similar mathematical techniques as in Ramsey (1928) to problems of depletion of resources in an economy.

However, the earlier models tended to ignore *exhaustible* resources in the technical possibilities of the economies under investigation. Dasgupta and Heal (1974) addressed this problem in their work that explored the immediate consequences of incorporating the *existence* of exhaustible resources in intertemporal planning, investigating the determination of the optimal rates of depletion of exhaustible resources and of investments in the economy. A major contribution of that work lies in its proposition that the substitution between reproducible capital and exhaustible resources is an important determinant of the characteristics of an optimal policy.[9] By explicitly accounting for exhaustible resources in the long-term planning model, they more directly address planning issues that are critical to many resource-abundant (and often resource-dependent) economies. In another study, Solow (1974) showed that the inclusion of the exhaustible resources component in the intertemporal planning models led to interesting results but did not significantly alter the basic theoretical principles. Much of the more recent work on economic planning in resource-abundant developing countries builds on the important contributions made by Dasgupta and Heal (1974), and Solow (1974).

Hartwick (1977) developed a rule for investing rents from non-renewable resources. According to Hartwick's calculations, an economy could sustain a maximal constant level of consumption through successive generations by investing all of the profits or rents accrued from exhaustible resources in reproducible capital, and by investing only this amount. While this rule directly addresses ethical issues of intergenerational equity, it also has consequences for economic growth and development. Sachs and Warner (1997) report high natural resource dependence as

[9] This proposition lies at the heart of models of optimal long-term growth in resource-rich economies.

one of three major structural conditions that dampen economic growth in Sub-Saharan Africa and outline a need to better understand the growth experiences of the few successful resource-rich developing countries.

Hamilton, *et. al*., (2005) in a follow-up to the earlier work, tested the Hartwick (1977) rule using data on investments and rents from exhaustible resource extraction for 70 countries. They found that, in general, applying the standard rule as development policy would have been extreme. However, they show that resource-rich countries, by following an even moderate saving effort, could have substantially increased their wealth. Of particular importance to our paper are the results form Hamilton, *et. al*., (2005) that show that Nigeria could have been five times as well off as it was in 2005, had it followed the Hartwick rule in the 30 years prior; and that oil would have played a much smaller role in the economy with likely beneficial impacts on the nonoil sectors. The potential for oil-dependent economies to use oil rents for the development of other sectors in the context of an overall economic development framework remains of interest to researchers and planners alike. However, the application of energy and economic planning models to Nigeria has not gone without its challenges.

Iwayemi in 1978 proposed the use of an investment planning model that used mixed integer programming methods to deal with investment resource allocation problems in the electricity sector in Nigeria. Making alternative assumptions on energy costs, and introducing a spatial dimension that accounted for the regional location of plants and the transmission of energy, he obtained an optimal generating mix from a set of fossil fuel and conventional hydro-plants to meet demand projected over three decades. The proposed model provided important insights into the characterization of energy investment and supply in Nigeria. However, Adamson in 1978 pointed out that energy planning in Nigeria in the 1960’s and 1970’s had largely ignored econometric forecasting models because, amongst other reasons, issues of data unavailability and inaccuracy rendered the models inapplicable to practical uses. Although, as suggested by Adamson, input-output and mathematical programming models fared better given (the effects of) the paucity of accurate data, these models in themselves were not unaffected by the challenges experienced with using econometric forecasting models in the peculiar planning environment. Other authors have proposed the use of multi-criteria programming methods for allocating energy resources among competing sectors of the economy. In particular, optimization models developed by the International Atomic Energy Agency (IAEA) have gained popularity in recent years (see ECN (2006)).

The older models for energy planning in Nigeria (e.g., Iwayemi, 1978) and the more recent modeling approaches (e.g., the IAEA models adopted for use in Nigeria), whilst providing important insights on the characterization of electricity demand and supply in Nigeria, may have considered the energy sector almost in isolation, largely ignoring important feedback with other sectors of the economy.

The present research departs from the earlier work by integrating established tools from natural resource economics into a framework of intertemporally optimizing representative agents from the macroeconomics literature. Further, following dynamic game theory, the present research more completely characterizes the planning environment of interest by modeling the strategic pursuit of goals by several agents in the resource-rich economy.

The Intertemporal Optimization Model

Our formulation of the energy planning model represents a practical compromise between introducing sufficient detail to capture the stylized facts of the energy sector and economy in Nigeria and accommodating limitations that exist in the data. We specify the behavior of intertemporally optimizing representative agents in the manner presented in Turnovsky (2000). In line with a time-dependent macroeconomic system, the model is formulated in continuous time. The model characterizes the behaviors of five different agents representing the government, publicly owned energy producers, multi-national companies involved in oil production, privately-owned local firms and households.[10] Following the set-up of an open-loop noncooperative (Nash) differential game, we assume that each agent takes the optimizing behaviors of the other agents as given in making her own decisions. Figure 3.1 depicts the representative agents specified in our model of the economy and demonstrates how analytical tools are integrated from related disciplines in economics.

While the interaction of the agents is depicted within a macro environment, micro- and institutional foundations underlie the individual sectoral specifications of the model. For example, microeconomic theory informs the characterization of the relevant producer and consumer decisions. The institutional structure of the Nigerian public sector informs our definition of the government agent behavioral function. Further, we incorporate the Pindyck (1978) model of the optimal exploration and production of nonrenewable resources in the natural resource management component of the economy to account for the activities of the oil industry.

In developing the economy-wide modeling framework, we have found persuasive arguments by Wymer (1993, 1997) for specifying and estimating macro-dynamic models as nonlinear stochastic differential equation systems. Wymer (1993) argues that small, highly aggregated models of this type, based on sound theoretical foundations, can account for a broad range of macroeconomic activity while remaining amenable to mathematical and statistical analysis.

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[10] The optimization problems of energy utilities and firms are given a static cast. This specification of these agents' decision behaviors is consistent with the two agents' not making choices affecting capital stocks; it also improves mathematical tractability of the model'.

In the spirit of this tradition of research in macro-dynamic modeling, we assume that the relevant macroeconomic activities in Nigeria can be characterized by a stochastic nonlinear differential equation system representing the behavior of five representative agents.

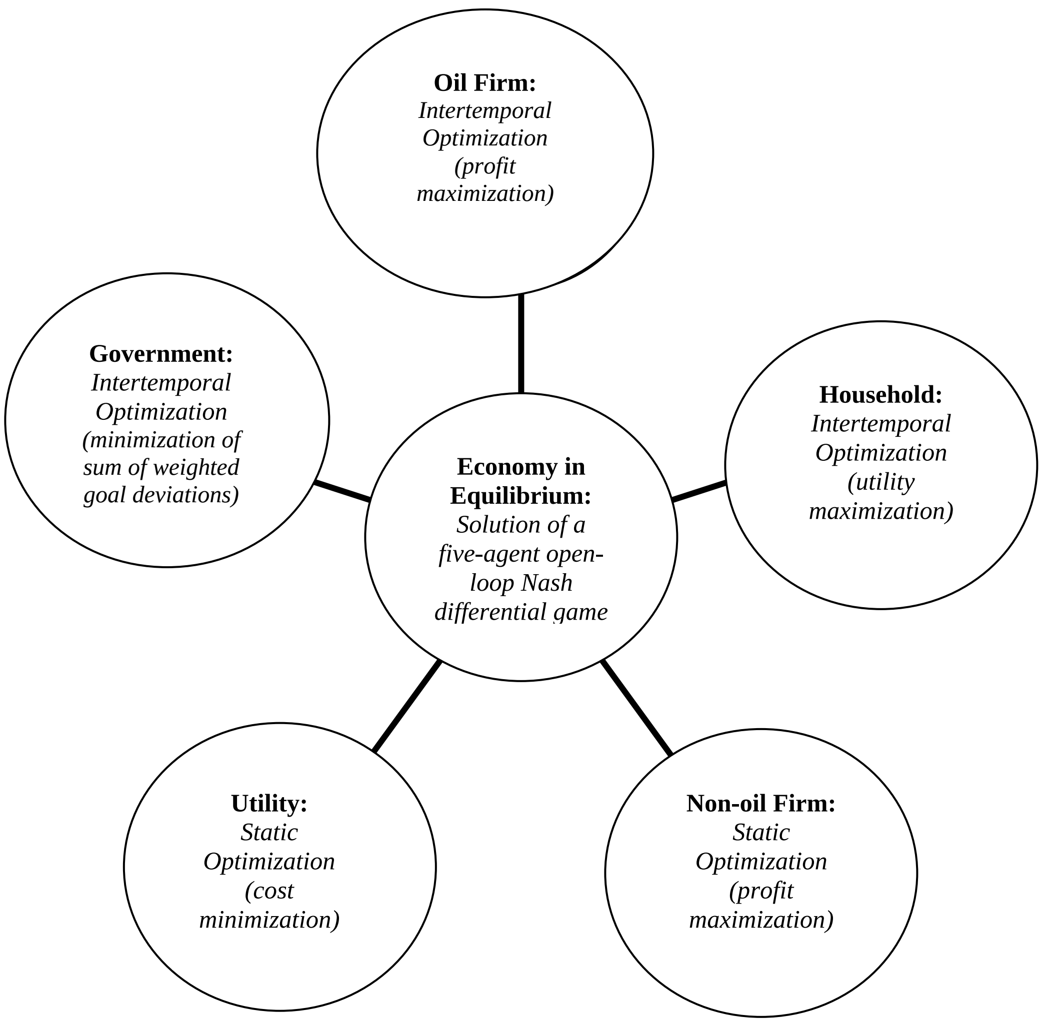

Figure 3.1: Representative agents in model of the economy and integration of analytical tools from related economics disciplines

Model Specification

We derive the equations specifying the model for the economy as the set of optimizing conditions for the stated objectives and technological and resource constraints faced by the representative agents. In our abstraction of the economy, a government agent owns capital, receives oil rents from the activities of foreign-owned oil companies and raises revenues from taxes on household income and the consumption of local and foreign goods and services. The government agent invests in the development of agricultural and human capital and is an investor in the energy sector, choosing its level of capital to fund electricity production. The representative agent for the petroleum sector is involved in oil and gas exploration and production. The electric utility agent uses natural gas generated by activities in the oil sector, along with labor and capital, as inputs in electricity production. The electricity utility in Nigeria is currently undergoing a deregulatory process where the government-owned establishment maintains responsibility for electricity generation while offering opportunities to local private firms to bid for the rights to operate transmission and distribution activities. We ignore this level of detail of industry operation in the current specification and assume that the single utility entity operates all aspects of electricity supply to firms and households. The household agent makes decisions on her consumption of energy and other local and imported goods. She invests in corporate bonds and foreign assets and derives income from interests accrued on these assets. The representative agent for the private local firm uses labor, electricity and capital inputs to produce output in the economy.

We next present the decision problems of the individual agents in some detail.

Government

The representative agent for the government chooses government consumption and investments in physical and human capital to minimize a weighted sum of deviations from policy targets for welfare and capital, subject to an intertemporal budget constraint. The objective functional and constraints are as in equations (3.2) through (3.9).

$$\underset{\{I_{anr},I_{sc},I_o,OD_g\}}{Min}\int_{t0}^{\alpha} e^{-\beta gt}\Big[\ 0.5\varpi_{g1}\left(K_{anr}-K_{anr_0}e^{\lambda 1t}\right)^2+0.5\varpi_{g2}\left(\Omega-\Omega_0 e^{\lambda 2t}\right)^2 + 0.5\varpi_{g3}\left(E_o^{ng}-E_0^{ng}e^{\lambda 3t}\right)^2\ \Big]dt \qquad (3.2)$$

s.t.

$$\Phi_g orev+arev+\dot{B}=OD_g+rB+I_{anr}\left(1+\frac{a_1 I_{anr}}{2K_{anr}}\right)+I_{sc}\left(1+\frac{a_2 I_{sc}}{2K_{sc}}\right) + I_o\left(1+\frac{a_3 I_o}{2K_o}\right) \qquad (3.3)$$

$$\dot{K}_{anr}=I_{anr} \qquad (3.4)$$

$$\dot{K}_{sc}=I_{sc} \qquad (3.5)$$

$$\dot{K}_o=I_o \qquad (3.6)$$

where

$$\Omega=(Ksc/Kf)^{\gamma w}\cdot(Y/pop)^{\alpha 1}\cdot ODg^{\alpha 2} \qquad (3.7)$$

$$Y=0.5\cdot\left(C+OD_g+I_f+I_{anr}+I_{sc}+I_o+orev-MGS+Y_f\right) \qquad (3.8)$$

$$arev=\tau_c\left(C+MGS\right)+\tau_y(r\cdot nfa) \qquad (3.9)$$

where the government agent chooses I_{anr}, I_{sc}, and I_o—her levels of investments in agriculture, social and community services, and other economic services—and OD_g, her levels of recurrent expenditure on goods and services.[11] K_{anr} is the accumulation of government capital in agriculture and can capture attempts to diversify the economy through investments in a non-oil sector with export potential. K_{sc} is capital accumulation in social and community services, a representation of development spending on human capital, and K_o is the capital accumulation in physical assets, including electricity generation capacity. Capital investments are assumed to be net of depreciation and equations (3.4) to (3.6) define physical constraints on net accumulation of human and physical capital. K_{sc} and K_o enter into the government objective function through Ω and E^{ng}, endogenous levels of welfare and electricity power generation, respectively. Ω is a mathematical expression transforming (the proportions of) social and physical capital, the levels of per capita national income and the amount of government recurrent spending into a measurable index of social welfare. (See equation 3.7.) It can be directly affected by the government agent. On the other hand, E^{ng}, the value of electricity generated by the public utility, is not endogenous to the government agent's optimization problem as it is determined in the optimization problem of the utility agent (discussed below). However, government investment in the public utility, K_o, is important in electricity generation in the utility.

K_{anr0} is a specified target level of capital accumulation in agriculture, while Ω_0 and E_0^{ng} are corresponding target levels for welfare and energy development that are a function of government spending on social and other services and capital investment in the energy sector. As shown in equation (3.7), Ω is also influenced by the levels of other variables not directly controlled by the government agent. K_f is the level of investments that households make in private (non-oil) local firms. Y is national income, defined as the value of gross domestic production (GDP), while Y_f is the

[11] Education, health and housing make up community and social services provided by the government. Other economic services include energy, water resources, construction, and transport and communication.

value of the net domestic output from the production function of the non-oil private firm (defined later for the local private firm), and *pop* denotes total population. The government seeks to minimize the period-to-period deviations from the target investment and social welfare levels.

In the intertemporal budget constraint specified in equation (3.3), the government expends income on capital (I_{anr}, I_{sc} and I_o) and recurrent (OD_g) projects. Costs of adjustments are imposed on period-to-period changes in the levels of physical stock and are assumed to be quadratic[12]. The adjustment costs serve two major purposes in the model. One, they impose a penalty on model solutions that represent substantial deviations in new investments from stable or long-term equilibrium path levels. Second, by introducing quadratic terms in investment costs, they ensure that the relevant control variables do not vanish from the equations that characterize an optimal solution to the agent's problem. (See an application in Donaghy *et al.*, 1999).

The government receives oil revenues, *orev*, from the multinationals; and taxes, *arev*, from households and non-oil firms. Oil revenues accruing to the federal government accounts are paid as a fixed proportion of the net proceeds from oil production (and exports), which are a function of the levels of oil production. Oil exploration and production in turn are set by the multinational (oil) company so that *orev* is taken as given in the set of equations for the government agent. Φ_g is the proportion of government income from oil revenues that is retained for government spending. This parameter has a value of one when there are no direct transfers of oil rents to citizens. Non-oil income (as shown in equation 3.9) includes taxes paid by households on local and foreign goods and on interests charged on assets held abroad. τ_c and τ_y are consumption and income taxes, respectively. The government also sells

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[12] The relevant quadratic function is $f_x(I_{x,}K_x) = I_x + a_x I_x^2 / 2K_x = I_x(1.0 + a_x I_x / 2K_x)$, where *x* represents the three forms of capital spending by the government, and *a* is the adjustment parameter associated with *x*.

bonds, B, to raise government capital (Equation 3.3). r is the discount rate in the economy and the rate charged on holdings of bonds.

MGS is the sum of imports of goods and services while Y enters into the equations in the model as the sum of the economy's activities (equation 3.8). C is the sum of household expenditures on local goods and services. The value of aggregate exports from all sectors is a function of X_0, the value of crude oil exports.[13] On average, ninety-five percent of the oil produced in the country is exported and oil exports historically account for ninety-five percent of all exports (EIU, various issues). I_f is the level of new investments in local (non-oil) private businesses, determined by the household agent; and DV is the change in the level of inventoried goods. All value terms are in *naira*, the local currency.

The model parameters ϖ_{g1}, ϖ_{g2} and ϖ_{g3} are policy weights on the accumulation of the three types of capital. These should be determined empirically in the model, as should be $\lambda 1$, $\lambda 2$, and $\lambda 3$, the time-dependent compounding factors assumed for the target capital accumulation, and γw, $\alpha 1$, and $\alpha 2$, the policy weights for the welfare variable (see equation 3.7) . The first-order necessary conditions for an optimal solution to the government agent intertemporal problem are presented in Appendix (3.B.1).

Multinational Oil Firm

Following Pindyck (1978), oil and gas firms are assumed to choose levels of exploratory and production activities. The firm seeks to maximize net revenues subject to cost relationships and restrictions on technology. We assume that the firm is able to augment its reserves at a rate that exceeds depletion of the resource in the short run.

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[13] Xo = P*Q, where P is defined as the real unit price of oil in Nigeria and is given by a price-dependent demand function, P = ($a - b \cdot Q$), where a and b are parameters of the price equation and Q is the quantity of oil produced, as defined for the oil firm agent.

The aggregate output from the oil industry activities is exported or sold locally[14]. We specify the optimization problem of the firm as in equations (3.10) to (3.12):

$$\underset{\{W,Q\}}{\text{Max}} \quad \int e^{-\beta t} \{(a - bQ) \cdot Q - (co/R)Q - (m + nW)\} dt \tag{3.10}$$

s.t.

$$\dot{X} = r_o W^s e^{-uX} \tag{3.11}$$

$$\dot{R} = \dot{X} - Q \tag{3.12}$$

where *Q* is the level of production activity; *W* is the level of exploratory activity (wells drilled); *R* is the known level of reserves of the resource and *X* is the cumulative addition of known reserves. The first term in the objective function, i.e., $(a - bQ) \cdot Q$ in equation (3.10) is the sum of gross revenues received by the oil firm, while (co / R) and $(m + nW)$ are the extraction and discovery cost functions respectively. An average (annual) producer price of oil is endogenously determined for Nigeria and is specified in equation (3.10) as $(a - bQ)$.

The change in the levels of cumulative additions to known reserves is defined in equation (3.11) as $r_o W^s e^{-uX}$, the discovery rate function. The discovery rate declines as exploration and discovery proceed over time; i.e., it becomes more and more difficult to make new discoveries (Pindyck, 1978). The parameters in the objective function, *a*, *b*, *co*, *m*, and *n*, are estimated from time-series data, as are the parameters from the discovery rate function, r_o, *u* and s. The parameterization of the Pindyck model is such that the price of oil decreases as supplies increase, for positive values of the parameter *b*, and the average cost of production increases—for positive values for *co* and *n*—as the proven reserve base is depleted, while exploratory costs

[14] Non-export sales include supply of crude oil to local refineries and of oil and gas to power stations.

increase with exploration.[15] First-order necessary conditions for the oil firm optimization problem are given in the Appendix (3.B.2).

Electric Utility

The electrical utility manager chooses the overall level of electricity generation, and levels of capacity utilization and natural gas and labor inputs to minimize costs, subject to technology and supply. We specify the optimization problem of the utility agent as in equation (3.13):

$$\underset{\{E_u, NG_u, L_u, CAPU_u\}}{\text{Min}} \quad p^g \cdot NG_u + w_f \cdot L_u + ucc \cdot CAPU_u \cdot K_u \tag{3.13}$$

s.t.

$$E_u^{ng} = \psi_u \cdot NG_u^{\partial 1u} \cdot L_u^{\partial 2u} \cdot \left(CAPU_u \cdot K_u\right)^{\partial 3u} \tag{3.14}$$

$$E_f + E_h + E_g \leq E_u^{ng} + \overline{E}_u^h \tag{3.15}$$

where the utility manager operates thermal and hydro-electricity plants. She chooses L_u and NG_u, the levels of labor and natural gas inputs to use, and E_u, the amount of electricity produced. She also determines the levels of utilization of installed capacity ($CAPU_u$), while *ucc* and K_o are exogenously determined levels of user cost and investments in electric power capacity, respectively. Output of electricity in the thermal plants, E_u^{ng} is represented by the Cobb-Douglas technology function defined in equation (3.13) so that $\partial 1k$, $\partial 2k$ and $\partial 3k$, the relevant production coefficients on natural gas, labor and capital inputs, sum to one. Additional electricity from hydro-resource units, $\overline{E}_u^h$, is assumed to be a fixed proportion of electricity produced in units

[15] Production costs increase as the proven reserve base is depleted to represent the increasing marginal costs of making new discoveries over time.

using thermal energy.[16] A final technical restriction on the utility's optimization problem is that the total grid electricity consumed by the public and private consumers does not exceed electricity produced by thermal- and hydro- stations. E_f, E_h and E_g in equation (3.15) represent electricity consumption by the government, residences and private firms. We present the first order conditions for the electric utility in the Appendix (3.B.3).

Households

In this model, residents are assumed to own all local and foreign capital used in production by firms. The household agent chooses levels of her consumption of energy and other goods and her levels of capital formation. The household objective is specified as an iso-elastic intertemporal utility function as in equation (3.16).

$$\underset{\{C,E_h,I_f,MGS\}}{MAX} \int_{t0}^{\infty} e^{-\beta ht} \left\{ \frac{1}{\gamma} \left(C \cdot MGS^{\eta 1} \cdot E_h^{\eta 2} \right)^{\gamma} \right\} dt, \ \eta 1, \eta 2 > 0, \ -\infty < \gamma < 1.0. \qquad (3.16)$$

s.t.

$$\dot{nfa} = \phi_h(orev) + (1-\tau_y)(r.nfa + Y) - (1-\tau_c)(C + MGS) - I_f(1 + \frac{\nu I_f}{2K_f})$$
$$- E_h \cdot P_e \qquad (3.17)$$

$$\dot{K}_f = I_f \qquad (3.18)$$

where the consumer chooses C, her aggregate level of goods consumed and E_h, her total household energy consumption in value terms. She also chooses I_f, her levels of investment in local private (non-oil) firms. The constraint on household spending is specified in equation (3.17). *nfa* denotes net foreign assets and is in form of foreign

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[16] Huge capital outlays for expansion projects and natural constraints on input availability make the year-to-year responses to energy demand more difficult to model in hydroelectricity facilities.

bonds held. τ_y and τ_c are taxes imposed on income and consumption while *r* denotes the rate of returns on foreign capital. The household agent receives a direct public fund allocation or income transfers in form of a fixed percentage (ϕ_h) of government revenues from the oil companies, *orev*. *Y* is gross domestic production and is determined in the model as firms' output so that it enters into the household optimization problem as an exogenous variable; *MGS* is the aggregate value of imports of goods and services, chosen by the households. As in the government agent optimization problem, quadratic costs of adjustments are imposed on changes to levels of capital owned by households—i.e. $(1+\nu_1 I_f/2K_f)$ in equation 3.17. Equation (3.18) denotes the physical constraint on the formation of household capital in firms. The relevant first-order conditions for optimization are presented in appendix (3.B.4).

Local Private Firms

The representative agent for firms chooses levels of capacity utilization and energy and labor inputs to maximize net revenues, subject to expected output demand and technology constraints. The optimization problem of the firm is presented in Equations (3.19) through (3.21).

$$\underset{\{E_f, L_f, CAPU_f\}}{MAX} P^{gdp} \cdot Y_f - \tau_{gg} \cdot GG_f - W_f \cdot L_f - P^e \cdot E_f - ucc \cdot CAPU_f \cdot K_f \tag{3.19}$$

s.t.

$$Y_f = \psi_f e^{\lambda_f t} (CAPU_f \cdot K_f)^{\delta_{1f}} L_f^{\delta_{2f}} K_{anr}^{\delta_{3f}} E_f^{\delta_{4f}} \tag{3.20}$$

$$GG_f = \psi_{gg} e - ^{\lambda gg} \cdot E_f^{\delta_{gg}} \tag{3.21}$$

where L_f is the firm's total demand for labor; E_f is energy consumed by the firm and $CAPU_f$ is the level of utilization of installed capacity, K_f. Net revenue for the firm is the value of its total production less the costs for labor, energy and capital inputs. W_f

denotes the unit wage rate; P_e is the price paid per unit of electricity consumed in production and *ucc* is the user cost of capital. The firm's output, Y_f, is produced following a Cobb-Douglas production function with energy, labor and capital as inputs. Further, taxes, τ_{gg} may be paid to the government on taxable levels of greenhouse gas emissions, GG_f. Finally, the level of greenhouse gas emissions resulting from the firm's production could be modeled as a function of the level of energy used as in equation (3.21). A negative value for λ_{gg}, the exponential factor in the greenhouse gas emissions equation could indicate, for example, a decrease in the ratios of emissions from energy inputs over time as 'cleaner' production technologies, are developed.[17] The relevant first-order conditions for optimization are presented in appendix (3.B.5).

Estimation of the Model

To employ the model specified above in simulation exercises, its parameters must be calibrated. Estimates of the parameters can be obtained by following Wymer's approach to estimating continuous-time models of intertemporally optimizing agents from discrete observations (Wymer, 1993, 1997; Donaghy and Wymer, 2011). According to this approach, a full-information maximum likelihood technique is employed, enabling algebraic restrictions on the coefficients of the model to be directly imposed during estimation. Once parameter estimates have been obtained, the qualitative properties of the model can be examined and alternative policy experiments conducted. This approach has been applied in other empirical settings (e.g. bi-lateral trade in Donaghy *et. al*., 1999 and environmental policy in Balta-Ozkan, *et. al*., 2007).

[17] The emissions tax function is only included in this specification to demonstrate the possibility for testing a government policy on emissions levels. Throughout, we assume zero taxes on greenhouse gas emissions in our model estimation and simulation exercises, ie., $\tau_{gg} \cdot GG_f = 0$.

An important feature of this approach is that the intertemporal optimization assumption of the representative agent is directly incorporated in the estimation algorithm (Wymer, 1997). The state and co-state equations characterizing a macro-dynamic equilibrium solution are solved such that relevant initial-value and transversality conditions are met that account for the effects of changes in resource endowments on the objective functional at every data point. As in Donaghy, *et. al*. (1999) and Balta-Ozkan, *et al*. (2007), estimation of the macro-dynamic model can directly incorporate the assumptions made of the representative agents into a three-step recursive solution procedure. In the first step, a set of 'observations' is generated on the unobserved variables and transversality conditions. For the first iteration, this generation of observations may be done by incorporating a set of plausible values of parameters – e.g., from theory – into numerical simulations. In the second-step, a variable-step, variable-order Adams method is used to solve intertemporal optimization problem characterized by the equilibrium conditions for each of the data points, given reasonable assumptions on parameter estimates and on the initial values of state and control variables. Relevant boundary point conditions are imposed on the state and co-state (unobserved) variables. The solution of the model must converge at every observation. The solutions for the unobserved variables are updated at every data point. For the variables for which historical series are available, the dynamic solution values are compared with the observed values. A variance-covariance matrix is formed (from the computed residuals). In the third-step, parameter estimates are then chosen to minimize the natural logarithm of the variance-covariance matrix by a quasi-Newton method. Parameter estimates employed in the first step are then updated. The solutions to the model for the specified time horizon are checked for convergence. Steps one through three are repeated if relevant convergence criteria are not met.

Application to the Empirical Setting

We have not yet been able to implement estimation of the full model as outlined above, but we have been able to estimate blocs of equations corresponding to the different representative agents. Blocs of equations were estimated with continuous-time methods with annual country-level data from 1980 to 2006. This length of the series represents the years for which we could obtain reasonably complete data to account for the representative agents' optimization problems specified for the macro-dynamic system. The time series that include data on income, production, consumption, investment and energy were obtained from publications of the Energy Commission of Nigeria and from various independent local and international data sources.[18] Table 3.2 presents a summary of selected series in our sample of 26 annual observations.

The selected period saw an increase in annual crude oil production from an average of about 540 million barrels in the 1980s to more than 800 million barrels on average, in the last decade for which data were available. As shown in Table 3.2, oil production peaked at 960 million barrels a year (in 2005). Crude petroleum revenues dominated all payments accruing to the government throughout, ranging from 64 to 86 percent of annual government income. Further, crude oil accounted on average for 95 percent of the value of all exports through the years (not shown in Table). The country's gross domestic production increased 206 percent in real value terms over the period of our sample series while the increase in installed capacity for electricity generation was more modest (170 percent). Total annual electricity consumption by the residences was 243 megawatt hours in 1980 and up to 1,195 megawatt hours by 2005, an increase in energy use over time that may depict growth in such factors as

[18] See Appendix C for a list of the data series as well as their descriptions, sources and modifications employed for the purpose of this research.

population, income, installed capacity and generation of electricity. Electricity consumption by firms similarly went up in the selected years. We find in the data that the capacity utilization in firms dropped from more than 70 percent in the early 1980s to about 44 percent on average in the last ten years, and 29 percent in 1995.[19] Time series of currency values were standardized to year 2000 values using the GDP deflator.[20]

The data for Nigeria posed significant challenges with respect to availability and quality. The periods for which data were available also may have been marked significantly with external and internal shocks that did not lend it readily to formal representation. For example, year-to-year inflation rates of up to 74 percent in the mid-1990s drove close to zero, the real values for some important variables such as wages received in the firm and utility sectors. As such, the potential for characterizing input demand in these sectors may have been seriously compromised.

Initial Model Experimentation and Simulation

To address issues of data unavailability and inaccuracy in the current modeling exercise, necessary simplifications were made to the original specification of the model. The most important of which was that the level of government recurrent expenditures less repayments of debt was defined exogenously (i.e., *ODg* in the set of government equations).

[19] Adenikinju (2003) reports that 61 percent of firm respondents in a 1998 nationwide survey estimated that power outages led to drops in their capacity utilization, of 10 to 50 percent.
[20] The TRANSF program in Wymer's suite of mathematical programs was used to prepare data for estimation.

Table 3.2: Summary statistics for selected Nigeria data series, 1980 – 2005[1]

Series	Unit and Scale[2]	Minimum	Maximum	Median	Mean	Standard Deviation
Gross Domestic Product	Billions, Naira	4,815.14	14,735.30	7,161.27	7,685.15	2,701.57
Government Recurrent Expenditure	Billions, Naira	184.36	1,117.73	456.75	558.69	257.95
Household Expenditure	Billions, Naira	3,415.93	8,716.88	4,265.13	4,957.76	1,666.61
Government Capital Expenditure:						
Agriculture and Other Non-Oil	Billions, Naira	5.68	92.24	20.50	34.17	28.40
Education and Social Services	Billions, Naira	17.99	302.55	51.28	64.07	56.79
Energy and Utilities	Billions, Naira	8.46	802.28	149.09	212.96	212.22
Crude Oil Production	Millions, Barrels	452.97	959.02	712.30	682.22	136.23
Revenues from Oil Production	Billions, Naira	599.21	4,762.40	1,165.34	1,623.47	1,084.03
Revenues from Non-Oil & Taxes	Billions, Naira	225.90	918.94	395.06	460.19	198.56
Electricity:						
Installed Capacity of Utilities	MegaWatts	2,419.90	6,538.30	6,268.30	5,438.55	1,302.26
Generation	MegaWatt Hours	815.10	2,779.30	1,672.85	1,620.13	521.40
Consumption (Households)	MegaWatt Hours	194.17	1,195.13	490.66	526.70	216.11
Consumption (Firms)	MegaWatt Hours	120.91	398.23	236.39	235.58	52.00
Capacity Utilization of Firms	Percent	29.30	73.30	40.35	42.94	11.25

[1] Various sources. See References for Appendix 3.
[2] Money values deflated using gross domestic product deflator. 2005 = 1.

The optimization problem of the government agent (i.e., equations 3.2 - 3.9) is re-stated as in equations (3.22) to equation (3.30) to reflect this change.

$$\underset{\{I_{anr},I_{sc},I_o\}}{Min}\int_{t0}^{\alpha} e^{-\beta t}\left[\ 0.5\varpi_{g1}\left(K_{anr}-K_{anr_0}e^{\lambda 1t}\right)^2+0.5\varpi_{g2}\left(\Omega-\Omega_0 e^{\lambda 2t}\right)^2 + 0.5\varpi_{g3}\left(E_o^{ng}-E_0^{ng}e^{\lambda 3t}\right)^2\ \right]dt \tag{3.22}$$

s.t.

$$\Phi_g orev + arev + \dot{B} = OD_g + rB + I_{anr}\left(1+\frac{a_1 I_{anr}}{2K_{anr}}\right)+I_{sc}\left(1+\frac{a_2 I_{sc}}{2K_{sc}}\right)+I_o\left(1+\frac{a_3 I_o}{2K_o}\right) \tag{3.23}$$

$$\dot{K}_{anr} = I_{anr} \tag{3.24}$$

$$\dot{K}_{sc} = I_{sc} \tag{3.25}$$

$$\dot{K}_o = I_o \tag{3.26}$$

where

$$\Omega = (Ksc/Kf)^{\gamma w}\cdot(Y/pop)^{\alpha 1}\cdot ODg^{\alpha 2} \tag{3.27}$$

$$Y = 0.5\cdot\left(C+OD_g+I_f+I_{anr}+I_{sc}+I_o+orev-MGS+Y_f\right) \tag{3.28}$$

$$arev = \tau_c\left(C+MGS\right)+\tau_y(r\cdot nfa) \tag{3.29}$$

$$OD_g = \alpha_g \exp(\lambda_{odg}t) \tag{3.30}$$

where α_g is a given starting value for government recurrent spending, *ODg*, that represents government recurrent expenditures (less debt repayment) in period (t = 0); and λ_{odg} is the assumed (average) growth rate of government spending over the relevant period, t. All other variables and parameters in the government bloc are re-stated as in equations (3.2) – (3.9).

We present the relevant parameters obtained from estimating the oil firm, utility and firm agents' modules in Table 3.3. Variables occurring as non-endogenous (i.e., variables other than the control) in any agent's optimization problem were modeled as forcing functions of time, with the forcing functions being estimated outside of the structural modules so that the resultant coefficients were independent of the parameters of the dynamic model of interacting agents (as in Balta-Ozkan, *et. al*., 2007).[21]

Model Simulation Exercise

Table 3.3 presents the parameters used in the simulation of the full model. These parameter values were either obtained from estimations of the independent agent blocs using available data (i.e., for the oil, local non-oil and energy utility firm modules) or deduced from the literature and following historical trends (i.e., for the government and household agents). These parameter values and given values of control and state variables were used to structure the simulation exercise with the full model. The calibrated zero- and first-order conditions of the optimization problems for the five agents were solved subject to boundary conditions over a relevant time horizon as a nonlinear system of simultaneous equations (see Appendix 3.B). The time-path solutions of the variables indicate how the economy might evolve, given the interrelationships between the agents. It is important to emphasize here that the solution of the current simulation exercise only represents possible future outcomes, given the model capturing of the historical trend. The values are not a prediction of future economic conditions.

[21] Forcing functions of time for the exogenous variables were estimated using the non-linear FIML estimation program ASIMUL and the blocs of equations corresponding to the different representative agents were estimated in ESCONA.

Table 3.3: Parameters of the modules for the Intertemporally Optimizing Agent Behaviors[1]

Parameter	Value	Parameter	Value
Government Agent:		*Oil Firm Agent*:	
$a1$	8.00	a	2.688
$a2$	20.00	b	1.655
$a3$	100.00	co	3.595
$\alpha 1$	0.75	m	-0.005
$\alpha 2$	0.25	ro	0.363
βg	0.03	s	0.500
$\lambda 1t$	0.02	u	0.003
$\lambda 2t$	0.02	n	0.0087
$\lambda 3t$	0.02	βo	0.018
λODg	0.03		
$\varpi g1$	1.00	*Private Firm Agent:*	
$\varpi g2$	1.00	$\delta 1f$	0.56
$\varpi g3$	1.00	$\delta 2f$	0.30
ϕg	0.96	$\delta 3f$	0.10
τc	0.06	$\delta 4f$	0.04
τy	0.12	ψf	2.16
γw	1.1	λf	0.02
Household Agent:		*Energy Utility Agent*:	
βh	0.03	$\delta 1u$	0.16
$\eta 1$	0.22	$\delta 2u$	0.33
$\eta 2$	0.09	$\delta 3u$	0.51
ϕh	0.04	ψu	1.80
ν	10.00	λu	0.02
γ	-0.10		

Following the evidence from the available data, the tax rates on consumption and income (i.e., τc and τy) were set at 6 and 12 percent, respectively. The assumed values for the adjustment costs on investment variables (i.e., ν, *a1*, *a2* and *a3*) were modified for the current exercise from upper bounds used in Barro and Sala-i-Martin (1995). Following the historical trend, real interest rate in the economy was pegged at 3 percent over the period for which the economy was simulated.

The parameters on the proportions of government oil revenues retained by the government or allocated to residents (i.e., ϕg *and* ϕh, respectively) denote a baseline agreement for oil revenue sharing in Nigeria. The parameters for government policy weights on capital accumulation (i.e, $\varpi g1$, $\varpi g2$ and $\varpi g3$) were arbitrarily set to 1.0, denoting equivalent importance for the types of capital. Other plausible values were derived from the data (e.g., $\eta 1$ and $\eta 2$) and from expert opinion (e.g., βg and βh).

Starting values for the unobserved variables in the model are presented in Table 3.4.

Table 3.4: Values for Unobserved Model Variables

Variable	Starting values defined for t = 0	t = 60
λ	-0.001	Undefined
ϑ	-7.1	Undefined
$\mu 1$	-0.02	0.0
$\mu 2$	0.18	0.0
ζ	-0.0003	Undefined
qganr	10.49	Undefined
qgsc	3.0	Undefined
qgo	22.8	Undefined

Next, we present in Table 3.5, the initial values for observed variables in the intertemporal optimization model. This set of values represents the values observed for a single observation of data. Typically, a data point (i.e., time, *t*) is chosen that is a viable candidate for a long-term equilibrium. This could be a period in the series for which important variables are somewhat stable from year to year. For our modeling purposes, starting values for the observed variables were chosen for year 1995 of the 26 years (1980 – 2005) of available time series data.

Table 3.5: Initial Values of Observed Model Variables

Variable	Description (Unit)[1]	Value at t = 0
B	Government debt	1.411
C	Household consumption	2.548
Ianr	Change in capital stock in agriculture	-0.900
If	Change in capital stock in firms	0.100
Io	Change in capital stock in utilities	0.200
Isc	Change in human capital investment	0.100
Kanr	Capital in agriculture	0.665
Kf	Capital in firms	6.816
Ko	Capital in utilities	2.938
Ksc	Capital in human development	0.889
MGS	Consumption of foreign goods	0.500
Nfa	Net foreign assets	0.071
ODg	Government recurrent expenditure	0.200
P	Price of oil (*Naira*)[2]	1.600
Q	Quantity of oil produced	0.700
R	Proven reserves of oil	17.900
W	Number of oil wells drilled	7.200
X	Cumulative additions of reserves	26.789
Y	Economy output	3.000
Ypf	Output from local nonoil firms	3.000

[1] Variable units are as reported in Table A.3 in the appendix; and are scaled as reported here for standardization of units in the model.
[2] Assuming 1995 real price and constant rice of USD 80 per barrel.

Results from the Initial Model Experimentation

The simplified model of the intertemporally optimizing agents was solved for a time horizon of 60 years from the initial period (t = 0). This length of time is considerable, given the level of complexity of agent and variable interactions in the model, and is consistent with the long-term window typically adopted for oil resource and development planning.[22] Relevant variables were relatively stable over the simulated period with immediate results indicating high importance of the household and government budget equations, both of which were defined as linear identities of

[22] However, the initial root mean squared error (0.206325) indicates room for improvement in the model fit to the generated data.

the agent's incomes and expenditures. The model's solution provides some information on such policy questions as the optimal rates of oil extraction and exploration in Nigeria. The results are for a baseline measure of direct oil wealth transfers to households and track investments in other (non-oil) sectors.

While no formal sensitivity analysis has been conducted at this stage of model development, the current specification of optimality conditions depicting relevant agent interactions was found to respond significantly to adjustment costs on investments. The solution paths of key variables are summarized below.

Optimal Oil Extraction and Exploration Rates

The model's determination of optimal production and drilling rates for the oil resource in Nigeria are presented in Figure 3.2.

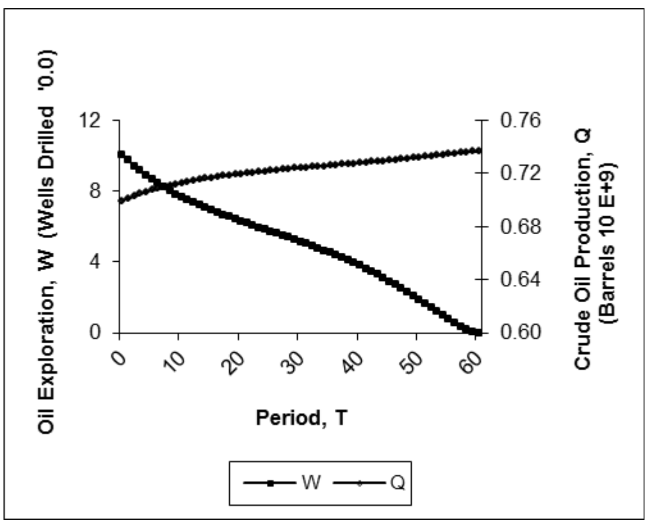

Figure 3.2: Optimal Crude Oil Production and Exploration: 60-Year Simulations

Based on the properties of the Nigerian economy as represented by the simplified optimization model, the year-to-year increase is expected to dampen over the simulation period while oil production increases. In particular, crude petroleum production increases every year by about 0.25 percent in the initial years of the simulation but this rate tapers to 0.05 percent on average in the last decade of the simulations (i.e. from years 50 through 60). In level terms, crude oil production starts out at over 699 million barrels annually (approximately 1,916 thousand barrels per day) in the initial time and rises roughly 5 percent over the forecast period, to about 2,018 thousand barrels a day by end of period. New oil drilling on the other hand is expected to fall rapidly. The results suggest that oil exploration would fall from a peak drilling rate at the start of the forecasts of around 100 new wells a year, to a new well being drilled every other year, in the terminal simulation period.

Crude petroleum prices move in the opposite direction of production so that the real price of oil decreases as an exponential function of time as output levels increase. Oil revenues in addition are sensitive to production and rise with increasing production (see Figure 3.3).

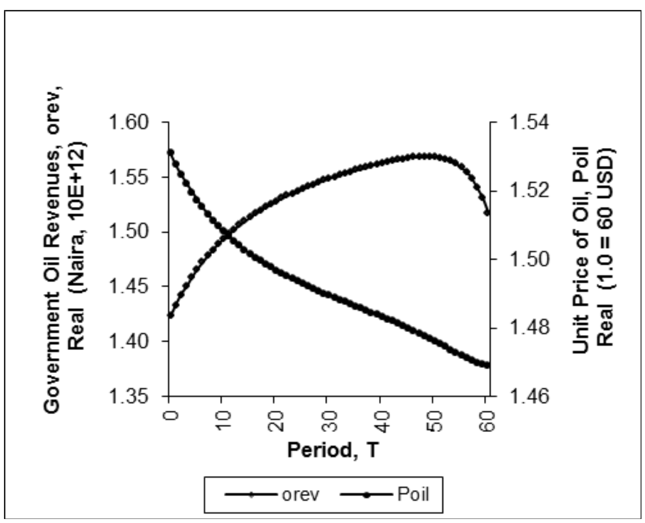

Figure 3.3: Oil Revenues and Real Prices of Oil: 60-Year Simulations

However, price reductions become sufficiently large as to counter the rise in income (following increased production), so that oil revenues dip at the end of the forecast period. The projected movements in oil prices and revenues are depicted in Figure 3.3. Oil revenues rise by up to 10.2 percent (from about 1,420 million local currency in real value) to the period (t = 48), after which revenues fall by up to 3.3 percent by the end of the forecast period. Oil prices on the other hand record a four percent increase through the period.

Output in Economy

From the solutions to the optimization model of the Nigerian economy, economic output increases substantially over the simulation period (see Figure 3.4). Output follows an increasing growth pattern almost throughout with an average growth rate of about 4.5 percent per year.[23]

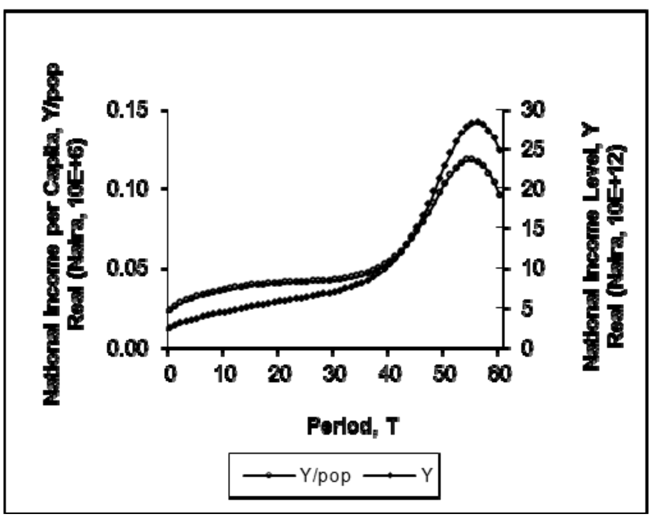

Figure 3.4: Level and Per Capita Output of Nigeria Economy: 60-Year Simulations

[23] Real GDP levels rise by 4.5 percent on average for over 5 decades, then drop by about 3 percent per annum on average over the last four years of simulations.

The intertemporal model solutions suggest an almost ten-fold increase in output by the end of the period. When compared with the expected growth in population, the increased output seems to pass on to improvements in the welfare of residents. An annual growth in population of 1.5 percent (based on United Nations projections) is accompanied by per-capita output increases of up to 2.4 percent per year on average over the simulations. However, the income per head falls by an average of 4 percent from year-to-year for the last five years of the simulations. This is consistent with the decreases in output observed for the overall output levels over the same period (see Figure 3.4).

Investment by the Government

In addition to the oil industry and general economy, important results come out of the government agent model. The levels of government investment in agriculture and human capital development are presented in Figure 3.5.

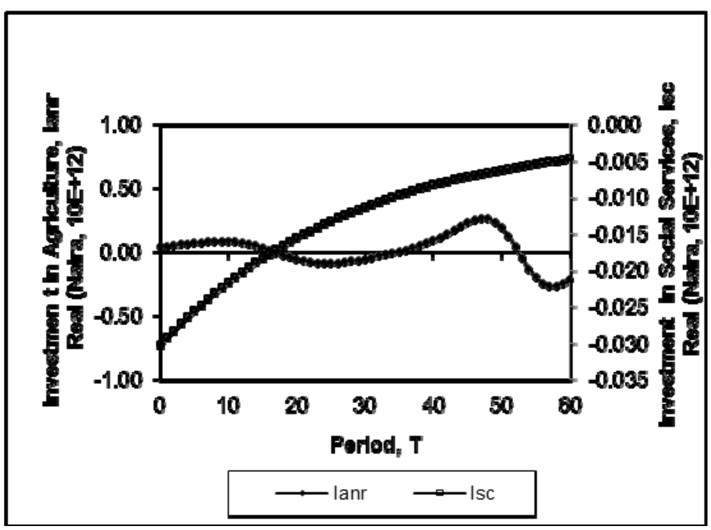

Figure 3.5: Investment in Agriculture and Human Capital: 60-Year Simulations

The level of capital spending in social and community services increases throughout, but at a decreasing rate, i.e., as more and more social capital is accumulated, the rates of new investments in this form of development are reduced. On the other hand, investments in agriculture and natural resources are almost level for a period, falling significantly several years into the future. This could suggest that, given the starting assumptions of the current model, increased government investment in the agricultural sector may not provide optimal use of limited public resources. More detailed modeling of the economy is however required to reach a more substantive conclusion on the prospects (or constraints) in general of directly transferring public funds into sectors of the economy to boost market-led economic growth.

The model solutions in addition provide information on the government agent investment in the public energy utility. The level of government investment in energy utilities is shown in Figure 3.6. According to our model solutions, investments in electricity production increase following an exponential function for more than a quarter of the simulation period, then declines at a more significant rate.[24]

The energy investment growth rates may not be inconsistent with huge lump investment patterns traditionally observed in the energy industry, particularly in developing regions such as Nigeria. The production of electricity associated with the levels of government investment in the industry as shown in Figure 3.6, is represented in Figure 3.7 below.

According to the model solutions, electricity production and consumption (not shown in figure) increase over time. While production declines at the end of the simulation period, it is still significantly higher than the unit level of electricity

[24]The late decline is most likely an artifact of the transversality condition on the capital stock of the energy utility.

produced in the initial year of the energy projections. This solution might underscore the need for improved electricity supply to support national economic development.

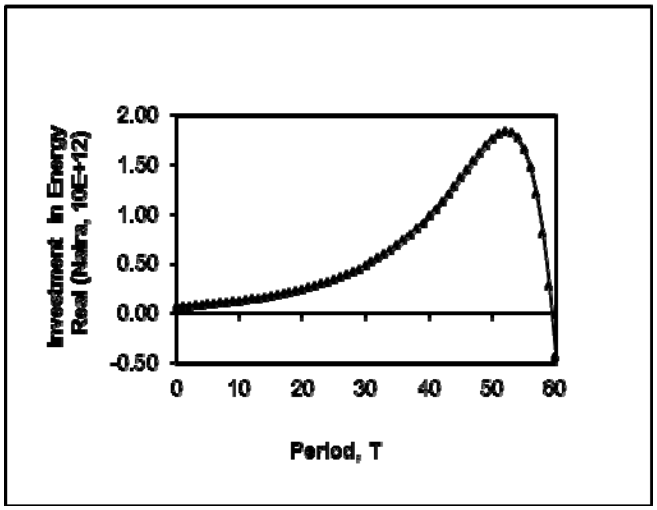

Figure 3.6: Investment in Electrical Utilities: 60-Year Simulations

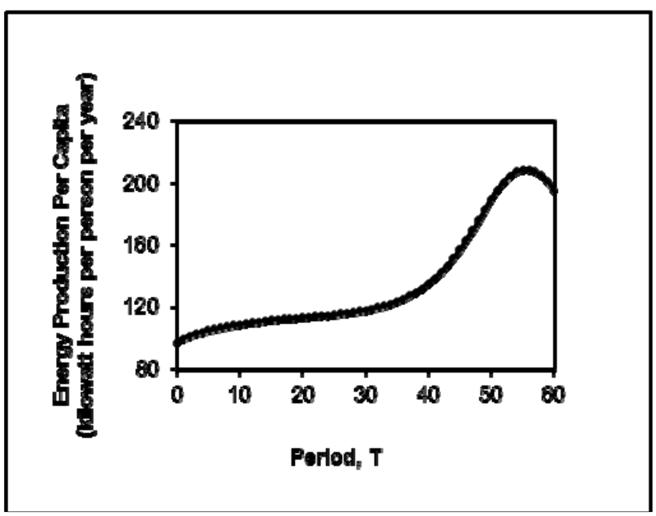

Figure 3.7: Electricity Production Per Capita: 60-Year Simulations

Household Consumption and Investment

Households in the optimization model respond to the improved levels of output and other economic conditions with increased spending on local and imported goods (see Figure 3.8). The year-to-year adjustments indicate monotonic changes that cause consumption to rise by about 32 percent through the end of the projections. Expenditures on local goods and services (including energy) increase at a faster rate than consumption of imports (see Figure 3.8).

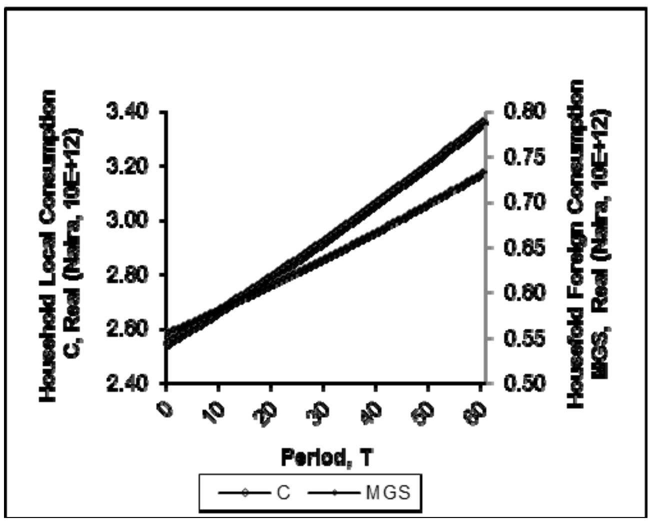

Figure 3.8: Households Consumption of Goods: 60-Year Simulations

Further, according to the model output, households increase their investments in local private firms through time (Figure 3.9). As shown in Figure 3.9, investments increase (or disinvestments decrease) from a period of no new investments in the local firm, to a relatively lengthy period of stable investment rates and finally, positive and increasing capital spending in local industry at the end of the model projections. The model solutions thus indicate increased transfers of household wealth into firm production in the latter years, consistent with increased production (and consumption) of locally- produced goods in the economy (refer to Figure 3.8).

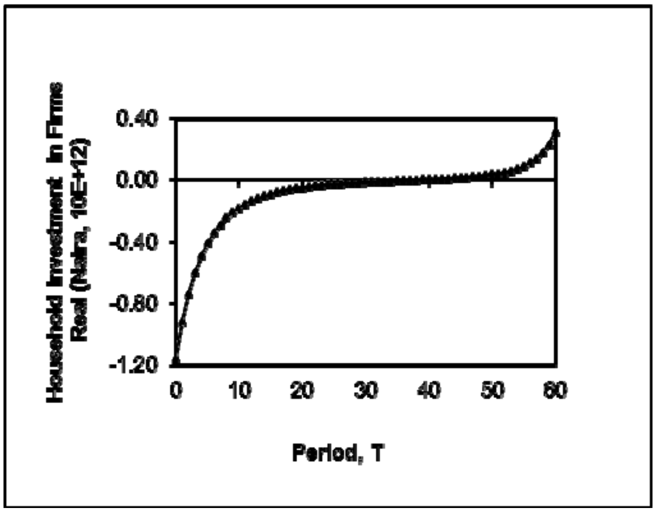

Figure 3.9: Household Investment in Firms: 60-Year Simulations

The solution paths of these variables further suggest that much of the increase in national income is transferred into ownership of foreign assets. (See Figure 3.10.)

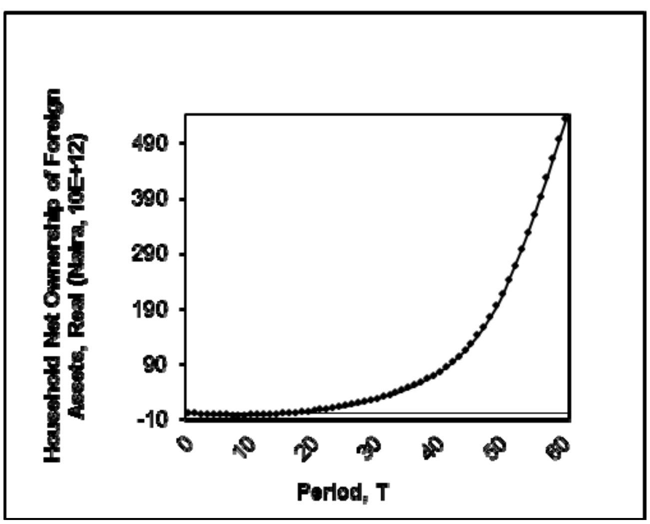

Figure 3.10: Net Foreign Asset Ownership: 60-Year Simulations

The model solution is sufficiently interesting to suggest continued development of models of this nature. As pointed out earlier, however, data and related challenges limit the immediate application of the current results to direct policy interpretation.

Summary of Results and Implications

The current research set out to apply recent developments in macro-dynamic modeling techniques to an energy-economy planning problem in Nigeria. The specification of the model of the economy accounted for the dependence of the economy on crude petroleum, a nonrenewable natural resource, and outlined intertemporal optimization objectives of distinct economic agents. The model specification allowed for the transfer of the wealth accrued from oil exports into capital expenditures on three major types of investments representing the government objectives for economic diversification (or the development of an alternative industry to oil export earnings); human capital; and local energy development. It also allowed for households to make investments in a local non-oil production or manufacturing sector and accounted for activities in a publicly-held energy utility. Components of the intertemporal optimization model were estimated for each of the economic agents to obtain model parameter values for a forecasting exercise. Plausible estimates were obtained for other parameters and unobserved variables from the literature. In addition, initial values of the observed variables were obtained from available data series using regression and similar techniques. Solutions to the model provided indicators on the optimal production and exploration rates for crude petroleum in Nigeria that are useful from a planning perspective. The solutions also suggest important information for investment in the various types of capital useful for socio-economic development.

Oil production increased over a 60-year planning horizon although year-to-year increases in production were observed to fall slowly. Optimal oil exploration rates declined at a much faster rate, decreasing to almost no new wells being developed at the end of the forecast period. Projections of oil prices showed expected declines in the future as optimal production increased. On the other hand, national (government) revenues from oil are expected to increase on average in association with the increased supply of the crude oil output, although declining prices at the end of the forecast period overshadow the effects of increased production so that total revenues from oil rents eventually decline. The results could indicate that the Nigerian economy is fast approaching a peak crude production level beyond which potential production could decline, given the reserves. Potential for reduced incomes from oil rents, in addition to further risks from external price shocks may state the case for increased diversification of the resource and economic base in Nigeria.

However, the results indicate that whilst it is optimal for the government to increase its levels of investments in human capital and energy development, increased direct involvement in agriculture and natural resources is not optimal. In particular, the model projections show level investments in agriculture and natural resources for a relatively lengthy period and significant declines into the future.

In the production sector, model projections show increased output and income in the economy on absolute and per capita basis. Households in turn respond with increased consumption of both local and foreign goods and services. National ownership of foreign assets is also increased. These measures together suggest improved levels of welfare in the economy. However, the results from the current modeling exercise are not directly applicable to policy interpretations.

Significant challenges were associated with using the data on Nigeria; i.e., concerning its availability and accuracy. Further, peculiarities of the Nigerian economy posed increased difficulties to the modeling (e.g., economy-wide shocks such as adjustment programs and their effects). For example, very high inflation in the mid 1990's led to the difficulties of dealing with near zero values for real wages in some years. That being said, the current modeling exercise did provide useful insights for the future development of techniques to address similar questions of resource extraction and rent allocation for development.

Further Development of the Model and Future Research

Immediate changes that could be made to the model to improve the characterization of the Nigeria economy and its application to forecasting and policy simulation include accounting more completely for interactions between and amongst the representative agents. For example, an attempt could be made to re-define the variable representing the government recurrent spending as an endogenous variable so that the direct effects of its changes can be explicitly accounted for in the household objective function.

Production in the (multinational) oil industry could be modeled to influence natural gas supplies (and production) in the public electricity sector directly. Currently, natural gas supplies for energy production in the economy do not account for useful gas produced (sometimes as a byproduct) alongside the crude petroleum output. Further, labor demand in households and non-oil firms should in a more complete characterization of the economy correspond to labor supplied by the households and should account for a proportion of the income coming to residents. However, improvements to the model need be accompanied with improvements in the quality of the data for meaningful progress to be made.

In a more advanced development of the present model, the level of interactions between the oil sector and the other economic agents could be increased further so that the model more completely describes the non-autonomous nature of the oil industry (i.e., from government regulation) and the involvement of households and local private firms in the oil industry.

APPENDIX 3.A

OBJECTIVES FOR NIGERIA NATIONAL ENERGY POLICY

1. Achieve national energy security and an efficient energy delivery system using an optimal mix of the nation's diversified energy resources.
2. Guarantee increased contribution of energy productive activities to national income.
3. Guarantee adequate, reliable and sustainable energy supply at appropriate costs and in an environmentally friendly manner, to the various sectors of the economy.
4. Guarantee an efficient and cost effective consumption pattern of energy resources.
5. Accelerate the process of acquisition and diffusion of technology and managerial expertise in the energy sector and indigenous participation in energy sector industries, for stability and self-reliance.
6. Promote increased investment and development of the energy sector with substantial private sector participation.
7. Ensure comprehensive, integrated and well-informed energy sector plans and programs for effective development.
8. Foster international co-operation in energy trade and projects development in Africa and in the world at large.
9. Promote international co-operation.

Source: ECN, 2003

APPENDIX 3.B

THE FIRST ORDER NECESSARY CONDITIONS

B.1: The Government

In addition to the 3 state equations defined in the text, the other first-order necessary conditions for the government agent are derived as in equations (B.1.1) through (B.1.8). The relevant boundary point and transversality conditions are in equations (B.1.9) through (B.1.12):

$$\partial H \big/ \partial B : \dot{\vartheta} = -\vartheta\left\{r \cdot \left(1-\tau_y\right) - \beta_g\right\} \tag{B.1.1}$$

$$\partial H \big/ \partial K_{anr} : \dot{q}g_{anr} = -\varpi_{g1}\left(K_{anr} - K_{anr_0} e^{\lambda 1 t}\right) - \vartheta\left(\frac{a_{anr}}{2} \cdot \left(\frac{I_{anr}}{K_{anr}}\right)^2\right) + \beta_{g \cdot} qg_{anr} \tag{B.1.2}$$

$$\partial H \big/ \partial K_{sc} : \dot{q}g_{sc} = -\varpi_{g2}\left(\Omega - \Omega_0 e^{\lambda 2t}\right) \cdot \gamma w \cdot \frac{\Omega}{K_{sc}} + \vartheta\left(\frac{a_{sc}}{2} \cdot \left(\frac{I_{sc}}{K_{sc}}\right)^2\right) + \beta_{g \cdot} qg_{sc} \tag{B.1.3}$$

$$\partial H \big/ \partial K_o : \dot{q}g_o = -\varpi_{g3}\left(E^{ng} - E_0^{ng} e^{\lambda 3t}\right) \cdot \delta 3k \cdot \frac{E^{ng} \cdot Pe}{K_o} + \vartheta\left(\frac{a_o}{2} \cdot \left(\frac{I_o}{K_o}\right)^2\right) + \beta_{g \cdot} qg_o \tag{B.1.4}$$

$$\partial H \big/ \partial I_{anr} : I_{anr} = -K_{anr} \cdot \left(1.0 + \frac{qg_{anr}}{\vartheta}\right) / a_{anr} \tag{B.1.5}$$

$$\partial H \big/ \partial I_{sc} : I_{sc} = -K_{sc} \cdot \left(1.0 + \frac{qg_{sc}}{\vartheta}\right) / a_{sc} \tag{B.1.6}$$

$$\partial H \big/ \partial I_o : I_o = -K_o \cdot \left(1.0 + \frac{qg_o}{\vartheta}\right) / a_o \tag{B.1.7}$$

$$\partial H \big/ \partial OD_g : \varpi_{g2}\left(\Omega - \Omega_0 e^{\lambda 2t}\right) \cdot \alpha 2 \cdot \frac{\Omega}{OD_g} + \vartheta = 0 \tag{B.1.8}$$

$$B_{(to)} = B_o ; \tag{B.1.9}$$

$$K_{anr(to)} = K_{anr} ; \quad K_{sc(to)} = K_{sc} ; \quad K_{o(to)} = K_o ; \tag{B.1.10}$$

$$\lim_{to \longrightarrow \infty} \vartheta e^{-Bt} B = 0\,; \quad \lim_{to \longrightarrow \infty} qg_{ag} e^{-Bt} K_{anr} = 0\,; \tag{B.1.11}$$

$$\lim_{to \longrightarrow \infty} qg_{sc} e^{-Bt} K_{sc} = 0\ ; \quad \lim_{to \longrightarrow \infty} qg_{o} e^{-Bt} K_{o} = 0\ ; \tag{B.1.12}$$

B.2: The Oil Firm

In addition to the 2 state equations defined in the text, the derived first-order necessary conditions for the oil firm include equations (B.2.1) to (B.2.4):

$$\partial H \big/ \partial X : \dot{\mu}_1 = (\mu_1 + \mu_2) \cdot u \cdot r_o w^s e^{-\mu X} + \beta_o \cdot \mu_1 \tag{B.2.1}$$

$$\partial H \big/ \partial R : \dot{\mu}_2 = -c_o q R^{-2} + \beta_o \cdot \mu_2 \tag{B.2.2}$$

$$\partial H \big/ \partial q : Q = (a - c_o / R - \mu_2) / 2 \cdot b \tag{B.2.3}$$

$$\partial H \big/ \partial w : W = \left\{ s \cdot (\mu_1 + \mu_2) \cdot r_o e^{-u \cdot X} / n \right\}^{1/s-1} \tag{B.2.4}$$

B.3: The Electric Utility

The first-order necessary conditions for the utility manager (in addition to the constraint equations defined in the text), choosing natural-gas and labor as inputs to minimize the cost of producing some targeted level of capacity of natural-gas based power, E_u^{ng}, are:

$$\partial H \big/ \partial NG_u : NG_u = \partial 1u \cdot \left(\frac{E^{ng} \cdot P_e}{P_g} \right) \tag{B.3.1}$$

$$\partial H \big/ \partial L_u : L_u = \partial 2u \cdot \left(\frac{E^{ng} \cdot P_e}{W_u} \right) \tag{B.3.2}$$

$$\partial H \big/ \partial CAPU_u : CAPU_u = \partial 3u \cdot \left(\frac{E^{ng} \cdot P_e}{ucc \cdot K_o} \right) \tag{B.3.3}$$

B.4: The Household

In addition to the 2 state equations defined in the text, the Hamiltonian system of equations for the representative agent of the household are defined in equations (B.4.1) to (B.4.21):

$$\partial H / \partial nfa : \dot{\lambda} = \beta_h \lambda - (1-\tau_y) \cdot (\lambda \cdot r) \quad \text{(B.4.1)}$$

$$\partial H / \partial K_f : -\dot{\xi} = -\beta_h \xi - \lambda \cdot \left[\upsilon / 2 \cdot (I_f / K_f)^2 \right] \quad \text{(B.4.2)}$$

$$\partial H / \partial C : \dot{C} = C / (\eta_1 \cdot \gamma + \eta_2 \cdot \gamma + \gamma - 1.0) \cdot (\beta_h - r \cdot (1.0 - \tau_y)) \quad \text{(B.4.3)}$$

$$\partial H / \partial MGS : MGS = \eta_1 \cdot C \quad \text{(B.4.4)}$$

$$\partial H / \partial E_h : E_h = \eta_2 \cdot C \cdot (1.0 + \tau_c) / P_e \quad \text{(B.4.5)}$$

$$\partial H / \partial I_f : I_f = -K_f \cdot \left(1 + \frac{\xi}{\lambda} \right) / \upsilon \quad \text{(B.4.6)}$$

$$\lim_{to \longrightarrow \infty} \lambda e^{-Bt} nfa = 0 ; \quad \lim_{to \longrightarrow \infty} \lambda e^{-Bt} (1 + \nu I_f / K_f) = 0 ; \quad \text{(B.4.7)}$$

B.5: The Private Local Firm

In addition to the constraint equations defined in the text, the first-order necessary conditions for the firm, choosing labor and energy inputs to minimize the costs of producing gross domestic product, *Y*, are as follows:

$$\partial H / \partial L_f : L_f = \delta_{1f} \left(\frac{Y}{W_f} \right) \quad \text{(B.5.1)}$$

$$\partial H / \partial E_f : E_f = \delta_{2f} \left(\frac{Y}{P_e} \right) \quad \text{(B.5.2)}$$

$$\partial H \big/ \partial CAPU_f : CAPU_f = \delta_{3f}\left(\frac{Y}{ucc \cdot K_f}\right) = 0 \tag{B.5.3}$$

APPENDIX 3.C: DATA DESCRIPTION

Table A.3: Description of the Nigeria Data Series

Variable	*Source*[1]	*Unit*	*Series Description and Modifications*
arev	CBN	Naira	Gross non-oil revenues
B	CBN	Naira	Sales of government bonds
			Derived: B = (rB / r)
C	EIU	Naira	Household expenditures (private consumption)
Capuf	CBN	Percent	Capacity utilization in firms
Capuu	CBN	Percent	Capacity utilization in utilities
			Derived: percent electricity generated of installed generation capacity
Cg	CBN	Naira	Government recurrent expenditures (government consumption)
Ef	CBN	mWh	Electricity consumption by firms
Eg	CBN	mWh	Electricity consumption by government
			(street lighting and government buildings)
Eh	CBN	mWh	Electricity consumed by residences
Ehu	CBN	mWh	Electricity generation from hydro facilities
Engu	CBN	mWh	Electricity generation from thermal facilities
Eu	CBN	mWh	Total electricity generation
Ianr	CBN	Naira	Capital expenditures on agriculture and natural resources
Ich	I&A	Megawatts	Installed capacity of hydro-electricity
If	IFS	Naira	Capital investments in firms
			(Gross fixed capital formation)
Io	CBN	Naira	Capital expenditures on other economic services
			(transportation, communication, construction and electricity)
Isc	CBN	Naira	Capital expenditures on social and community services
Lf	ILO	Units	Labor employed in firms
			Derived: manufacturing (percent of) GDP*employed persons over age 15

Table A.3 continued

Variable	*Source*[1]	*Unit*	*Series Description and Modifications*
Lu	ILO	Units	Labor employed in public utilities
			Derived: utilities (percent of) GDP * employed persons over age 15
MGS	EIU	Naira	Imports of goods and services
NFA	EIU	Naira	Net foreign assets (commercial banks)
Ngu	NNPC	Cubic feet	Natural gas used in electricity generation (as fixed proportion of gas produced)
orev	CBN	Naira	Gross revenue from crude petroleum
			(international and local sales, petroleum profit tax and treaties)
Pe	CBN	Naira	Unit price of electricity produced
Pgdp	EIU	Unit	GDP deflator (2000 = 1)
Png	CBN	Naira	Unit cost of natural gas used in electricity production
Poil	CBN	Naira	Unit cost of crude petroleum; Derived
r	CBN	Percent	Discount rate
R	EIU	Barrels	Known levels of crude oil reserves
rB	CBN	Naira	Recurrent expenditures on government debt
trn	CBN	Naira	Capital investments on transfers
ucc	IFS	Percent	User cost of capital
	NBS;		Derived: Interest rate plus depreciation less inflation
W	NNPC	Units	Number of oil wells dug
Wf	CBN	Naira	Average annual wage paid in the private sector (manufacturing)
Wu	CBN	Naira	Average annual wage paid in the public sector
X	EIU	Barrels	Cumulative additions of known oil reserves
			Derived: Xt = Xbar + Xt-1, where Xbar = Rt - Rt-1 + Qt for t = year
Xo	EIU	Naira	Value of crude oil exports
Y	EIU	Naira	Gross domestic production, deflated (2000=1)

[1] Sources : CBN, EIA; EIU; I&A: Ibitoye and Adenikinju; IFS; ILO; NBS and NNPC. See References for Appendix 3.

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