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ASSESSMENT OF NEW YORK'S POLLUTION DISCHARGE ELIMINATION PERMITS FOR CAFO'S: A REGIONAL ANALYSIS

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Abstract

In this paper, we apply mathematical programming methods to account explicitly for restrictions on land application of nutrients from large dairy operations in New York and to analyze the effects on measured outcomes of farm management adjustments to the nutrient policy and to recent changes in relevant agricultural prices. Based on a set of unique data, we assess the effects of new regulations for nutrient management by confined animal feeding operations (CAFOs) on farm income, land use, manure and fertilizer management, and 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 adjustments to dairy rations 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. In a related paper, we demonstrate that while the CAFO regulations correct for this problem, the reductions in the risks of nutrient loadings could be accompanied by losses to farm income. Our current application to an important dairy production region in Western New York further buttresses this point. We also demonstrate that farm net revenue is sensitive to the availability of nearby land suitable for manure disposal. Since 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, crops with higher potential to absorb field nutrients are more attractive than would otherwise be the case. The shadow prices for CAFO land with low soil phosphorus increase, reflecting not only the value of land for crop production but also its value as a site for manure disposal. These shadow prices reflect what the CAFOs could pay for additional land, and this price falls as the distance to the CAFO increases.

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Background

As in some other states, New York is in the midst of revising its State Pollutant Discharge Elimination System (SPDES) Permits for Concentrated Animal Feeding Operations (CAFOs). The purpose of these permits is to limit the application of manure on cropland to mitigate the possible effects on water quality from the improper management of animal waste. There is general agreement that these limits should be set at the agronomic nutrient crop requirements. Since animal waste generally contains more phosphorus than nitrogen relative nutrient demands for most crops, the State's proposed CAFO regulations limit manure application based primarily on phosphorus crop requirements. The revised regulations are likely to lead to increased need for off-site disposal of animal waste.

These revised regulations come against a backdrop of other recent events that have placed added pressure on the operating margins of livestock and dairy producers, such as the global recession-driven reduced demand for livestock and dairy products and high prices for feed ingredients. While feed prices fell in 2009 below the previous year's record-highs, they have remained well above historic levels. This has led to adjustments in farm and feed management practices.

Some dairy producers, for example, have shifted to raising a larger share of their feed requirements, and they have also explored options for including nontraditional feed ingredients such as distillers dried grains and solubles (DDGS) in their dairy feed rations. In Western New York, the somewhat surprising local availability of DDGS, and the possibilities of increased supplies from an expanding bio-fuels industry have made more attractive the prospects for incorporating these low-cost alternative ingredients in dairy feed rations. However, some research does suggest that inclusion of the less conventional feed ingredients could also increase the potential for phosphorus loading to the environment.[2] Since they limit manure application based primarily on phosphorus crop requirements, the State's CAFO regulations could also limit dairy producers' opportunities to utilize some new low-cost feed ingredients.

Objectives

In this paper, we investigate the important linkages between the State's proposed CAFO regulations, particularly those related to restrictions on land application of nutrients from animal wastes and the other farm management adjustments precipitated by other recent events that have affected agricultural prices and have placed added pressure on the operating margins of large dairy producers in New York. Since management responses to these changes in the market conditions and in environmental regulations are not apparent in existing agricultural data, we investigate these issues through a mathematical programming model constructed for an important dairy production region in New York State. The model accounts for the new

[2] For ratios of animals to cropland typically found on dairy farms in central New York, Schmit, *et. al*. (2009) estimate that only about 60% of the manure produced is needed meet the crop nutrient requirements. They also determine optimal levels of DDGS in total mixed rations as the price ratio of DDGS to corn varies. At price ratios where DDGS is fed only to heifers and dry cows, N in manure in excess of crop requirements increases only by about 6% relative to when no DDGS is fed, while iP_2O_5 in excess of crop requirements increase by 39%. When the price ratio falls to where DDGS is also fed to lactating cows, N in manure in excess of crop requirements increases by 68% relative to when no DDGS is fed, but P_2O_5 in manure in excess of crop requirements increases by 110%.

restrictions on land application of phosphorus (P) and nitrogen (N). The new restrictions are based on comprehensive nutrient management plans (CNMPs) that CAFOs must develop to obtain and maintain the necessary pollution discharge elimination permits from New York State.

In the analysis of the effects of these new nutrient management regulations, we focus on the changes in farm incomes, changes in land use, and 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 disposed of off-site of the CAFOs in response to the increased regulations may well end up on nearby farms that are not directly affected by the restrictions.

Our research is unique in several respects. By explicitly modeling the dairy operation from a whole-farm nutrient management perspective that is consistent with nutrient management restrictions established in cooperation set by the relevant Land Grant University (in this case Cornell University), it is one of the first attempts to assess the impact of these 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 phosphorus and nitrogen application where the risk of runoff is high and 3) prohibit the application of manure and/or commercial P where agronomic soil test phosphorus (STP) on cropland is excessive.

Furthermore, through a set of non-linear constraints in the model, we allow for the endogenous determination of the nutrient composition of manure from feeding combinations of animal rations. This is a particularly important characteristic of the model due to anticipated adjustments to the dairy rations that are driven by recent high prices for conventional feed ingredients and the likelihood that nonconventional feed ingredients may be substituted into the rations. Absent any regulation, the substitution of these feed ingredients may well lead to increased phosphorus and nitrogen content of the manure that could exacerbate environmental quality problems as CAFOs dispose of manure either on the farm, of off-site.

The reduced opportunities for the application of manure to cropland could increase the costs of off-farm manure disposal. We account for the cost implications of transporting manure to off-farm recipients in detail. As off-farm manure disposal costs rise, available farmland on which additional manure can be applied and that is in close proximity to CAFOs may take on added value as a manure disposal site. Our study is unique in that we specifically document, both analytically and empirically, the differential effects of the several restrictions on the application of nutrients on the value of cropland. As is evident in the analysis below, these differential values are derived analytically by a carful examination of several of the Kuhn-Tucker first-order necessary conditions for an optimum. These differences in the value of cropland arise primarily because the CAFO restrictions on nutrient application through manure differ depending on the soil test P (STP). These differential land values also depend on the crops' fixed N and P requirements, the endogenously determined N and P concentrations in the manure, and the net costs of off-site manure disposal. Because the restrictions on nutrient application differ depending on STP, so do the proportions of the value of cropland attributable to value of crops produced and attributable to the land's value as a waste disposal site.

Our analysis is made possible through the availability of two unique data sets developed for agricultural production regions in New York State. The first contains data on the distribution of cropland on dairy farms according to soil productivity class, while the second contains multi-year summaries of soil nutrient tests on cropland throughout the State. Without access to this latter data set it would have been impossible to identify the proportions of cropland in the study region that fall into the several STP groups on which the proposed CAFO regultions necessary in Using these data and results from previous research, we are able to incorporate into our model empirical methods for estimating nutrient go on to estimate the effects of the regulations on the distributions of phosphorus 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.

Below, we begin with an outline of the new proposed nutrient restrictions for CAFOs in New York State and then summarize important characteristics of the New York dairy producing region that is the focus of our analysis. This discussion is followed by a description of the mathematical framework for our regional model and details of its empirical specification. Throughout this discussion, we contrast the specification needed for a base scenario and how the model must be extended to reflect the new CAFO nutrient application standards, to account for changes in the costs of off-site manure disposal, and to measure empirically the phosphorus 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 application regulations and a policy scenario in which we simulate the new nutrient application regulations. Finally, we discuss the implications of our findings and offer conclusions that can be drawn from this study.

Soil Nutrient Regulation and Management in New York

The Clean Water Act of 1998 is the primary Federal legislation that requires operators of certain animal-feeding operations to develop comprehensive nutrient management plans (CNMPs) to minimize the detrimental effects of their operations on water quality (USDA-EPA, 1999; USDA-NRCS 2003a).[3] As highlighted by Kaplin, *et al*. (2004), the current regulatory landscape is embodied in a Unified Strategy that outlines the actions that the USDA and the EPA are to take under existing legal and regulatory authority to mitigate the actual and potential water quality impacts posed by animal production. Revisions to the regulations changed the requirements for an NPDES permit and their associated Effluent Limit Guidelines for CAFOs by requiring permit holders to develop and implement nutrient management plans for manure nutrients. These nutrient management plans limit the land application of manure.

The setting of realistic crop yield objectives is central to USDA's criteria for implementing nutrient management plans. Thus, limits are generally agreed to be the agronomic nutrient demand on cropland—i.e., manure generated at CAFOs is applied to cropland and pastureland at a rate no greater than the rate at which the crops can assimilate the applied nutrients, thereby minimizing nutrient runoff from the fields. In implementing these nutrient management plans, the states have some flexibility to adapt to local conditions, which, for example, can be based on

[3] 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).

recommendations for the optimal rates of soil nutrient applications from the appropriate Land Grant Universities.

In New York State, CAFOs must develop and implement a CNMP in order to obtain the necessary state pollution discharge elimination system (SPDES) permits (NYSDEC, 2003). [4] The CNMPs are guided by the Natural Resources Conservation Service (NRCS) Code 590 standard to ensure that the crops receive adequate nutrients while minimizing nutrient losses to surface and ground waters (USDA-NRCS, 1999). Since fields differ in their potential for environmental nutrient loading, two indicators developed at Cornell, the Phosphorus Runoff Index (PI) and the Nitrogen Leaching Index (NLI), aid in determining the susceptibility of fields to nutrient losses (Ketterings, *et al*., 2003a and 2003b).

As outlined by the Cornell University nutrient management program, our modeling of the nutrient restrictions on P and N for field crops in New York limits crop nutrient applications to the agronomic uptake levels. We assume that a P-based management strategy must be followed on soils where the PI is the relevant index, i.e., where P loss is considered the larger threat of nutrient loading. Otherwise, the NLI is the important index and an N-based management strategy must be followed.

As seen in Figure 1, P-based management is followed on fields considered to have *high* STP (i.e., a soil Morgan P test of 40 lbs/acre and greater) or *medium* (i.e., a soil Morgan P test of from 9 to 39 lbs/acre) risks of phosphorus run-off. While no manure or commercial P fertilizer is allowed on high P soils, application of P is restricted to no more than 40 percent of the crop P-removal rates on fields with a *medium* phosphorus index. On all other fields, those with low STP soils (i.e., a soil Morgan P test of less than 9 lbs/acre), the application of P is limited to crop P-removal rate.[5]

In contrast, under N-based management, manure and commercial fertilizers can be applied at rates to meet recommended nitrogen crop requirements, including volatilization losses.[6] For acres on which corn is grown, N application cannot exceed the requirements for optimum productivity for all three classifications of land based on the soil P test.

There is more flexibility on land in alfalfa that typically meets its nitrogen requirements through N fixation. N fixation activity is reduced when other sources of N are readily available perhaps 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 (Ketterings, *et al*., 2006). Therefore, since manure P application for alfalfa up to the crop's phosphorus requirements is allowed on the *low* and *medium* STP soils, some nitrogen is simultaneously applied. In

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[4] Gollehon, *et al.* (2001) report that more than 50 percent of the excess manure nitrogen and two-thirds of the excess manure phosphorus generated nation-wide are produced on CAFOs.

[5] There is currently a new view that P should be regulated by Psaturation (Knight, et al., 2012). According to this method only 5% of New York soils are at 20% saturation which is a Morgan P-test of 86lbs. This is higher than our 40lbs. cutoff for high P-test, but given the small fraction of high P soils in the state, there can be only a small fraction of soils where the ranking would be different un der Psaturation and out corrent methods. Clearly, some further research into the differences would be useful.

[6] Typically, this application regime results in the over application of phosphorus, whereas P-based nutrient management tends to make the application of nitrogen fertilizers necessary (USDA-NRCS, 1999).

recognition of the high potential for P loss, no manure can be spread on alfalfa planted to land with a *high* STP.

To account explicitly for manure and fertilizer nitrogen and phosphorus restrictions on CAFOs, we incorporate soil test results for land into mathematical programming models for a three-county dairy production region in New York. 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 effects of the policy are evident through a comparison of the programming solutions.

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. The Genesee River, with its source in Pennsylvania, runs about 157 miles northward mostly through New York, from where it drains into Lake Ontario. 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 1, we summarize descriptive data from the latest U. S. Census of Agriculture for the three-county study region available from the USDA.

Wyoming County has the largest number of large animal feeding operations of the three counties, with 27 farms with 500 or more dairy cows and 61 farms with 200 and more dairy cows.[7] Livingston County, with the smallest number of large dairy farms, 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 about 1,420 acres per CAFO. Cropland not controlled by the CAFOs in the region is estimated to be about 2,380 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 of all manure production even when field nutrient restrictions limit the application on land over which they have direct control. However, regional cropland not controlled by the CAFOs is not necessarily available for use as manure receiving sites. Location, ease of access, spatial fragmentation of cropland 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 application.

[7] 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.

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 (e.g. Feinerman, *et al*., 2004; Hadrich, *et al*., 2008; Kaplan, *et al*., 2004).

Using a regional optimization model, Kaplan, *et al*. (2004) provide important insights into the linkages between land nutrient restrictions and the local economy and environment. They use a constrained partial equilibrium model to illustrate the effects on sectors of the economy of imposing nutrient standards on the largest of AFOs. By adopting a nation-wide approach that includes the major USDA's farm production regions, the study accounts for regional differences in the policy effects due to differences in CAFO concentrations (and manure production) and land availability.[8] Results from that study suggest that the costs of meeting the land nutrient standards are passed on to local consumers of in the form of higher prices.

In contrast, Feinerman, *et al*. (2004) determine the response of manure demand to nutrient standards in Virginia. These manure demand relationships are incorporated into a highly stylized spatial equilibrium model to estimate the welfare costs of alternative soil N and P application standards for manure application. These authors assume that crop farmers with no animal production can use manure (produced by the animal feeding operations) or commercial fertilizers to meet their crop nutrient needs. This demand for manure by the crop farms is assumed 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 are composed of the purchase prices at the supplier's gate and the costs of transportation to the recipient fields.[9] The model accounts for three strategies for manure and fertilizer application; two sources of farm manure; three possible scenarios for nutrient regulations; and a cropland availability constraint that limits manure application in the short-term. The major limitation of the analysis is its short-run focus where manure supply from

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[8] In their analysis of economic and environmental implications of restrictions on nutrient applications to cropland, Kaplan, *et al*. (2004) examine the implications of alternative assumptions about the willingness of crop producers to accept manure as a substitute for commercial fertilizer.

[9] Manure suppliers could be from regulated CAFOs with insufficient land to on which to spread manure. Farm gate manure prices include costs for storage and soil tests.

poultry producers is completely inelastic. The model does not allow for any for production changes or feed ration changes in response to the regulations that could influence longer-term manure production and supply.

Hadrich, *et al*. (2008), on the other hand, allow 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 demonstrate the possibility of formulating animal feed rations that 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 previous studies, our mathematical programming model used in the assessment of soil nutrient regulations is state-specific; it is based 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 alternative specifications of the model for a base and a nutrient policy scenario isolate the effects of the nutrient regulations. In the analysis, we link our model to bio-energy feed ingredients, feed prices and manure nutrient loadings using the CPM-Dairy program.[10] We accommodate the potential lower-cost feed alternatives as in Schmit, *et al*. (2009) so as to assess the whole-farm nutrient management and planning response given DDGS in feed rations.

By applying techniques developed by Vadas, *et al*. (2009), we use the solutions to our non-linear programming model to estimate phosphorus loss in runoff due to the application of manure and commercial fertilizer to cropland. The methods by Vadas, *et al*. (2009) to estimate P loss in runoff are based on extensive field studies and for a variety of soil, fertilizer management and climate conditions, and they are designed to be compatible with ground water transport models such as the Erosion-Productivity Impact Calculator (EPIC).

The Base Model

To assess changes in farm income, nutrient management, land use and land values, and environmental quality associated with the combined effects of new nutrient standards and changing feed prices for our three-county dairy producing region, we must first 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. 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.

[10] 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.

The model is designed to maximize expected annual revenues over expected variable costs of the CAFO's within the study region.[11] Thus, 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 for the model reflect important production, cost and revenue relationships for the dairy CAFO operations. [12] Key features of the model are a livestock component that determines production as well as feeding activities and a crop component that assigns acres to various crops, accounts for restrictions due to necessary 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. Thus, 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. A scaled-down proto-type of the model is presented in Appendix A (Tables A1 and A2).[13] The model also differentiates between the production of agricultural commodities and their uses. Crops grown on farmland owned or rented by the dairy operation can be sold or in some cases be fed to animals produced on the farm. Separate activities are also defined for the purchase of all feed ingredients and for major inputs such as labor, fuel and fertilizers.

The dairy farms in our model reflect the makeup of typical regulated CAFOs in the dairy production region, with characteristics similar to those of equivalently-sized farms participating in the Cornell Dairy Farm Business Summary program (Knoblauch, *et al*., 2008). The dairy CAFOs in the selected three-county region have about 80 thousand dairy cows and control 157 thousand acres (37 percent) of the harvested cropland in the region (Table 1). Up to 1.6 million hours of on-farm labor are estimated to be available annually and additional off-farm labor can be hired at two different wage levels. Farm labor is used in livestock production and in feeding activities, as well as in crop production, including the application of commercial fertilizer and manure to cropland.

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

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[11] The structure of the model is similar to that in Schmit, *et al*. (2009) and in Enahoro (2010).

[12] 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 sale of farm-grown crops.

[13] As discussed in greater detail below, this proto-type is also used to facilitate an analytical derivation of the differential implications of the new restrictions on land nutrient applications and increases in the costs of off-farm manure disposal for the internal value of cropland. The results from of this derivation can be generalized to the larger model is a straightforward fashion.

and the numbers of dry cows, heifers, cull cows and cull calves are constrained to be in appropriate fixed proportions.

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). Through the structure of the model, we determine how the composition of final feed rations are affected by relative prices of the component feed ingredients. The 10 separate dairy cow activities in the model 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 rations are reported in detail by (Enahoro, 2010).

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. 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 in 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 are assumed to follow crop 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. Restrictions are also imposed on the crop rotations since these crop rotations influence field crop requirements for nutrients (see Enahoro (2010) for details).

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 accounts 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 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 categories.[14] 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 from either manure or commercial fertilizer. The nutrient composition of

[14] 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 are taken from Rao *et al*., 2007. The soil P test distributions are assumed to be the same across the soil productivity classes.

manure is determined endogenously in the model, and it depends on the compositions of the feed rations for lactating and dry cows and for young stock. Crop requirements not met by manure nutrients can be purchased as commercial 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. The amounts of N and P nutrients produced in the manure are similarly accumulated. Manure produced on the farm is spread on crop acres or is transported to off-farm locations. Not all of the manure nutrients produced on the farm are available for plant uptake and we account for handling, storage and field losses. 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.

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. We base these restrictions on the 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). These distributions are reported in Table 2.

Based on the survey data, we model 7 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, 53 percent of the land is in the medium STP category and allows for only 40 percent of the crop P requirement to be met from manure and commercial fertilizers. The remaining 40% of the land has a low STP and can receive soil amendments up to its entire P needs.

In general, soils with medium or low STPs receive manure at application rates for which either of P or N requirements of the crop is fulfilled, whichever is more limiting. The nutrient requirements beyond those supplied by manure at this rate are then supplied from purchases of commercial N or P, whichever is needed.

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 for disposal. We accommodate this in the regional model. These alternatives account for the differential costs of manure disposal off-site. 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.[15]

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 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. 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, 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 as:

$$TC = C_{DM} + C_{MS} - V_{MP} - V_{MN}$$

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.[16] 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

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

[16] 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.

things being equal) equivalent to the market price of fertilizer P and N.[17] 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}).[18]

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 values 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 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 the equation above). 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 for doing so are given in Appendix B.

Empirical Results

To generate the empirical results, we examine a number of solutions to our programming models for a range in feed prices. 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 rise in feed prices while basing our analysis on a price set that may be more sustainable into the near future we make use of recent available 5-year average prices (i.e. 2005-2009) at the time the empirical research was conducted. If relative input and output prices,

[17] 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 cannot 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.

[18] 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.

however, have remained about the same in years since then, the model solutions may remain similar, ans would the implications for changes in net returns.

Results from the Base Model
At the 5-year average prices for production input and output, it is optimal for the CAFOs in the region to raise an average of 724 cows and 564 replacement heifers. The lactating cows are fed a corn silage-based ration that contains 10 percent DDGS [on a dry matter (DM) basis] with an 8 percent fat content. Dry cows are 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 fed to the farm animals, but some is also sold.

In this base case, the total production of manure averages 29.3 tons per cow. In this manure, there are per cow averages of 71 and 183 pounds of P and N, respectively. All manure produced is applied to the land as nutrients. In so doing, 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.

In Table 3, we summarize the major revenues and costs associated with this base case in which no nutrient standards are in effect. Total receipts from sales of crops, livestock and milk (less payment made for milk marketing) average $3,752 per cow. Milk sales account for 87 percent of all farm proceeds. Variable production costs account for about 69 percent of the gross farm revenue, with the largest proportion going to the purchases of feed (i.e., $1,046 per cow).

The costs of manure and nutrient management are only a fraction of the total production cost outlays, only $47 per cow.

Results for the Policy Scenario
We also use 5-year average prices (i.e. 2005-2009) as the relevant prices in the model solutions that simulate 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.[19] 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 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.

[19] 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.

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 in the nutrient policy scenario are also shown in Table 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 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.[20] 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 needs to 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 4.

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.

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.[21] Manure and fertilizer application in the regional dairy model are compared for eight policy scenarios that reflect successively higher costs for off-site manure disposal (see Table 4). We also include the base policy solutions

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[20] 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.

[21] 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.

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).[22]

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.[23]

As shown in Figure 2, 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 4).

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 5. 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.

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 5). 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.[24] 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

[22] 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).

[23] 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 that are no greater than one mile.

[24] 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.

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.[25] 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 6).

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 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.

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 A), cropland on CAFOs has 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 3).

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

[25] 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.

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

A Safety-First Interpretation of Changes in Nutrient Loadings

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 can be stated formally for P and N loss in runoff as:

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[26] 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.

$$\Pr\left(P_{RO} > P_{\alpha}\right) \le \alpha$$

$$\Pr\left(N_{RO} > N_{\alpha}\right) \le \alpha$$

where the expressions in these two equations denote that the probability that P (N) runoff (and leaching), P_{ro} and N_{ro}, exceed critical thresholds P_w and N_w with only a small probability α. The probability of extreme storms occurring is given by α, and it 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. $P_{\alpha}\,(N_{\alpha})$ is obtained from estimates of P (N) loading for the sample of 30 weather observations and is the average P (N) loss in runoff (and leaching) from all cornfields. For the purpose of assessing environmental regulation, $P_{\alpha}\,(N_{\alpha})$ would indicate the lower limit on the amount of P (N) runoff that occurs for a set level of probability, α. An efficient environmental quality policy should reduce these values of $P_{\alpha}\,(N_{\alpha})$ value by a significant amount. Levels of $P_{\alpha}\,(N_{\alpha})$ are compared in our analysis for the base and policy scenarios. For purposes of illustration, we focus on the P (N) loadings between the base scenario and a policy scenario in which there is a $4/ton cost for off-site manure disposal.

To facilitate this safety-first interpretation of our results, we must compare the cumulative distributions of P (N) loading over the thirty years of weather data for the base and policy scenarios. We do this comparison by plotting the estimates of P (N) loss in runoff associated with the model simulations against the probabilities of their occurrence of weather data. Before the 30-year distributions are plotted, the estimates of P runoff are ranked from low to high for the base and the policy scenarios as in Figure 4. Similarly, cumulative distributions of nitrate runoff and leaching are plotted for the base and nutrient regulations scenarios as in Figure 5.

Environmental quality improvements following regulations on land nutrient applications are evident because the cumulative distributions of P (N) runoff for the policy case lay below those 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 they are in the base case.

To illustrate this safety-first interpretation of our results, to the model results, we assume an arbitrary cut-off of 10 percent for the probability of extreme weather occurring; i.e., α = 0.10; in Figure 4 and Figure 5, this point is 0.90 on the horizontal axis.

Reading (off the vertical axes) the estimates of nutrient loadings that correspond to this point for the base and policy runoff distributions are the lower limits on the amounts of nutrient losses that could only occur with a 10 percent probability (i.e., $P_{\alpha} \mid \alpha = 0.1$). 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 of phosphorus per acre (Figure 4). 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 is evident from Figure 5, 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 of N per acre in the base case, and 7.1 pounds of N per acre under the policy simulation. As with P loading, however, these results may indicate that significant risks of nitrate loss to the environment still remain 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 the STP falls. Conversely, successive additions of manure and or fertilizers to lower P soils could raise the P levels on those soils so that the STP levels on all soils may tend to converge over time.

There are two primary implications of such a convergence of STPs over time. 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, the internal values of cropland of similar qualities should converge.

Conclusions

Regional mathematical programming models are developed to assess the implications of new nutrient standards for land nutrient application on confined animal feeding operations (CAFOs) in New York. We explicitly account 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 allow 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 allow for the assessment of the differential effects of the new CAFO nutrient restrictions and alternative manure disposal costs on internal values of farmland of different productivities, and with different initial amounts of phosphorus in the soil.

In response to high prices of traditional feed ingredients, our model solutions indicate 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 increase the levels of nitrogen and phosphorus in the dairy waste, and where manure is applied on fields as crop nutrients, nutrient applications exceed 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 indicate that the land nutrient regulations mitigate the excess nutrient problem. However, while the new regulations reduce nutrient loadings by about half on average, a safety-first interpretation of the results suggest that significant risks of nutrient loss to the environment could remain during severe weather events. Our results also indicate some that net returns per cow of CAFOs would decline under the new regulations by between 3% and 15% depending on what is assumed about the cost of off-farm disposal of manure.

As outlined in Figure 1, the new nutrient restrictions differentially restrict the application of P and N from manure and commercial sources based on high medium and low soil test P (STP). Based on these nutrient requirements, more than half of the manure produced on CAFOs in the dairy-producing region must be 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 is 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 farmers should take advantage of flexibilities in the nutrients regulations by growing more alfalfa than corn on soils that could receive more manure under the regulation. Alfalfa provides more conducive conditions for spreading manure because of its inherent agronomic characteristics. Alfalfa thus increases in value as a field crop 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 shadow values on farmland shadow demonstrates that cropland 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 additional value as a site for manure disposal. The effect of the nutrient policy on CAFO land is more pronounced as the costs of off-site manure disposal costs increase. In particular, as the manure disposal costs increase, the shadow prices of the low STP soils (that allowed for substantial manure application) controlled by CAFOs increased significantly in relation to the value of land on which no or minimal P applications are allowed.

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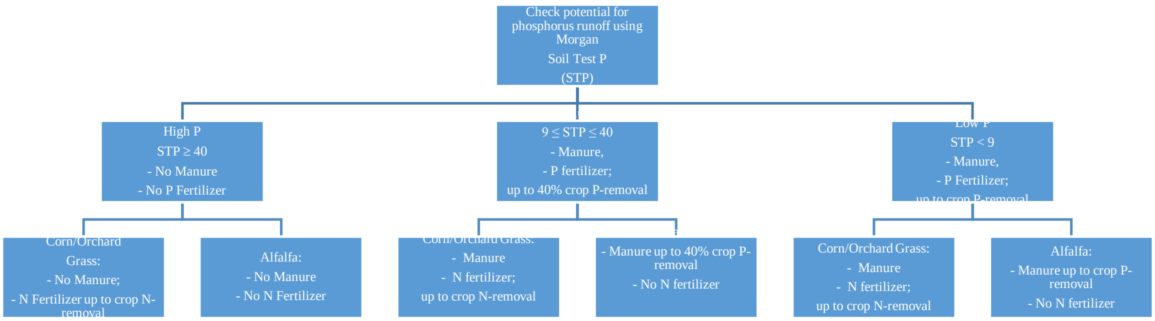

Figure 1. Phosphorus and Nitrogen phosphorus management for field crops following nutrient standards in New York

Table 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
CAFO land/Cow (ac./cow)	1.95	1.93	1.98	-	1.96
Other land/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] Regional means are weighted averages for the three counties.
[4] Cropland in the region not controlled by CAFOs. Location is unknown.

Table 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.

Table 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.

Table 4: 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.

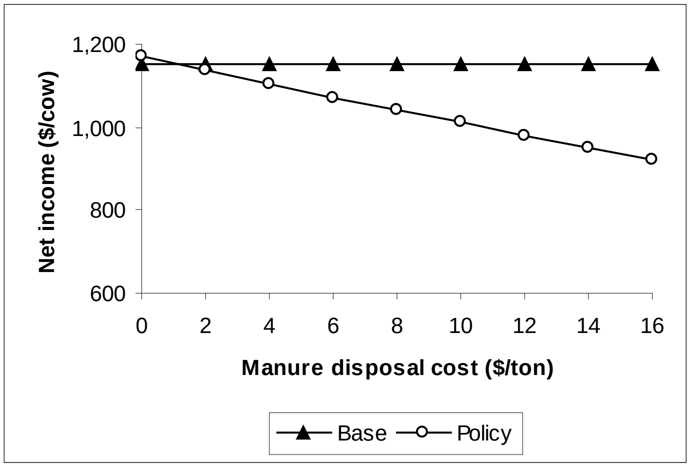

Figure 2. Net returns for alternative manure disposal costs

Table 5: 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 Class 1	163	163	163	163	163	163	163	163	163
Land Class 2	468	468	468	468	324	324	324	324	324
Land Class 3	78	78	78	78	78	78	78	78	78
Alfalfa:									
Land Class 1	163	163	163	163	163	163	163	163	163
Land Class 2	468	468	468	468	612	612	612	612	612
Land Class 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 represent 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 test P
[4] Since P is not restricted, STP distinctions are not relevant for the base case. Cropped acreages reported follow the soil distribution assumptions.

Table 6: 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.

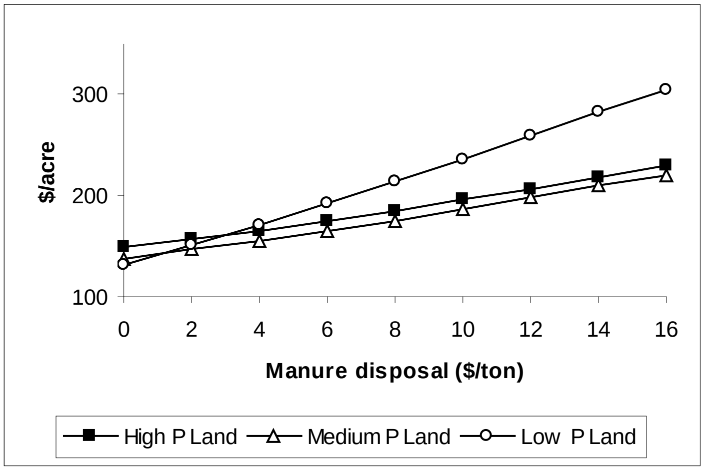

Figure 3. Shadow value of land under nutrient policy

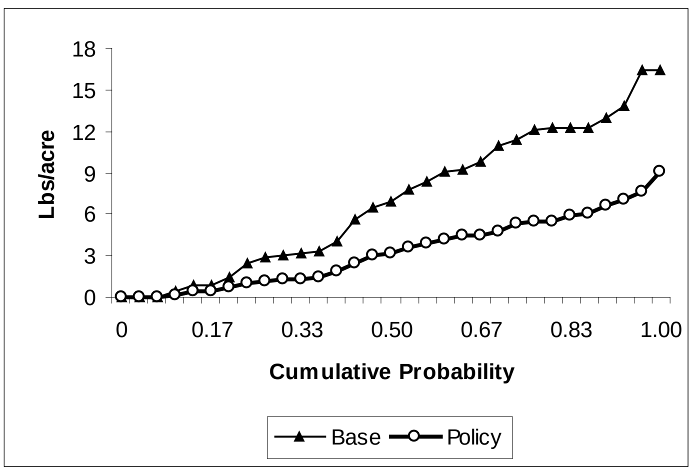

Figure 4. Phosphorus loss in runoff from corn fields

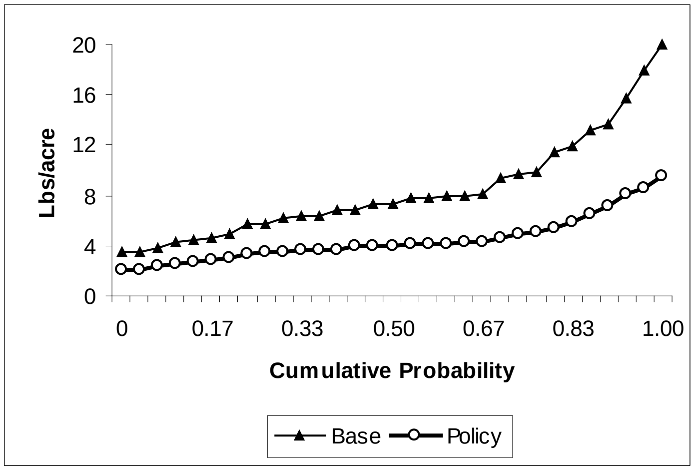

Figure 5. Nitrate loss in runoff and leaching from corn fields

Appendix A
Implications of Restrictions on Manure Application by CAFOs for the Internal Value of Cropland

The new policy on field nutrient application influences regulated CAFOs in at least two major ways. First, dairy operators are forced to recognize nutrients inherent to the soil in their fertilizer and manure management decisions. Second, they must dispose of manure produced by the farm animals in excess of the soils' capacity to receive manure nutrients off the farm. It is also likely that the economic effects of the restrictions on nutrient applications will be reflected in agricultural land values, and as the costs of off-site disposal rise, these effects may differ for land in close proximity to CAFO operations.

In this appendix we explore the nature of these effects analytically through a stylized version of the optimization model employed in the study. We do this through a careful examination of how the shadow prices of land are affected by the nutrient application restrictions and the costs of off-site manure disposal. This stylized model includes only those elements of the non-linear programming model that have direct bearing on differences in the shadow prices of land. The results generalize to a more complex model in a rather straightforward fashion.

The Stylized Non-Linear Programming Model

The parameters and activities for this stylized model are defined in Table A.1, and the structure of the model is in Table A.2. We can begin to understand the structure by examining the objective function in Equation (A.1) in Table A.2. For simplicity, and with no loss of generality, we need only include two dairy cow activities. These activities differ by the amounts of corn (equation (A.2)), alfalfa (equation (A.3)), and other feed (equation (A.4)), in the rations. Corn and alfalfa for feed can either be purchased or grown, while other feeds (e.g. such as DDGS) must be purchased.

With this model structure, the amounts of N and P in the animal manure are determined endogenously in the model. Total manure production is accumulated by equation (A.5). The amounts of N and P in manure are accumulated in equations (A.6) and (A.7), and their concentrations in the manure ($\delta_N = N_M / M$ and $\delta_P = P_M / M$) that is spread on corn and alfalfa are reflected in equations (A.8 and A.9) and equation (A.10 and A.11), respectively. In addition to the nutrients supplied by the spreading of manure, these constraints allow for the nutrient requirements for corn and alfalfa also to be met totally, or in part, from purchased N and P. In equation (A.12), we account for the total volume of manure, which must either be spread on cropland or disposed of off-site (*DM*).

In this stylized model, we specify three types of crop land, but for purposes of the analysis below, we assume that crop yields and nutrient requirements are identical. For policy purposes, these land types are distinguished solely on the basis on their soil test P (STP) as indicated in Figure 1 of the text. This construction facilitates the analytical derivation of the differences in the internal value of land because the CAFO restrictions on nutrient application through manure differ depending on the STP. As becomes clear in the derivation, these internal land values also depend on the crops' fixed N and P requirements, the endogenously determined N and P concentrations in the manure, and the costs of off-site manure disposal.[27] Because the nutrient applications restrictions differ, so do the proportions of the internal value of cropland attributable to the value of crop production and attributable to its value as a waste disposal site.

Analysis of Land Shadow Prices

To understand how the new nutrient regulations for CAFOs influence the economic value of crop land, it is necessary to examine in detail some of the Kuhn-Tucker necessary conditions for an optimum. These are derived from the Lagrangian function in Table A.3, and are reported in Tables A.4 and A.5, depending on the expected sign on the Lagrangian multipliers. To illustrate the effects analytically, we focus on the internal value of land in corn production. These results are similar in principle to those that would come from our more complex empirical model, but in that model, the internal values of land are also affected by the necessary 4-year corn and hay crop rotations.

After some rearranging, the Kuhn-Tucker necessary conditions from above that are needed to understand the shadow prices for land become:

$$L_{ACi} : \lambda_C Y_{Ci} \leq C_{Ci} + \lambda_{NCi}\eta_{Ci} + \lambda_{PCi}\rho_{Ci} + \lambda_{Li} \qquad (i = 1, 2, 3) \qquad \text{(A.33')}$$
$$L_{SMCi} : \lambda_{NCi}\delta_N + \lambda_{PCi}\delta_P \leq C_{SM} + \lambda_{MSD} \qquad (i = 1, 2, 3) \qquad \text{(A.35')}$$
$$L_{BPCi} : \lambda_{PCi} \leq C_P \qquad (i = 1, 2, 3) \qquad \text{(A.31')}$$
$$L_{BNCi} : +\lambda_{NCi} \leq C_N \qquad (i = 1, 2, 3) \qquad \text{(A.29')}$$
$$L_{DM} : -\lambda_{MSD} \leq C_{DM} \qquad \text{(A.37')}$$

To begin the analysis, we must interpret each of these equations. Because manure can either be spread or disposed of off-site and there are several uses for crop output and several sources of N and P, these outputs and inputs are valued internally, with market prices placing upper or lower bounds on these internal values. Thus, equation (A.33') assures that the internal value of the corn output from an acre of land *i* in corn must be no greater than the variable cost of production inputs plus the sum of the internal values for the remaining inputs, land *i* and the N and P input requirements. From equation (A.35'), we know that the combined internal value of N and P in manure is no greater than the sum of the cost of spreading and the internal value of disposing manure off-site. Two of the remaining three equations, (A.31') and (A.29'), ensure that market prices for P and N are effective ceilings on the internal of these respective nutrients. Equation (A.37') ensures that the internal value of manure disposal is bounded from above by the cost of disposal.

The Two Cases for Analysis

To see how the internal values or shadow prices of land are affected by the nutrient restrictions, we must consider two cases: A base case and a policy case.

[27] As mentioned in the text, the empirical model also distinguishes three types of cropland based on land productivity. The results from this appendix would generalize in a straightforward way across different qualities of cropland.

In both cases, it is also reasonable to assume initially that corn is grown on land *i*, that is $A_{Ci} > 0$, (for *i= 1, 2, 3*). Then, from the complementary slackness conditions (equation (A.65) from Table A.6), we know that equation (A.33') holds as an equality: the internal value of corn production is equal to the internal value of the inputs needed in production. Rewriting, we can solve for the shadow price of land *i* as:

$$\lambda_{Li} = \lambda_C Y_{Ci} - C_{Ci} - \lambda_{NCi}\eta_{Ci} - \lambda_{PCi}\rho_{Ci} \qquad (i = 1, 2, 3) \qquad \text{(A.33')}$$

Since we have a single soil productivity class in this example, lands 1, 2, and 3 are distinguished only by the soil test P (STP). Therefore, in both cases, we can assume that, Y_{Ci}, the corn yield per acre is constant for all *i* (i.e., $Y_{Ci} = Y_C$ for *i=1, 2, 3*), and that the variable costs of production—except for nutrient requirements—are constant as well. (i.e., $C_{Ci} = C_C$ for *i=1, 2, 3*).

Furthermore, if we also assume that manure is spread on corn land *i*, $SM_{Ci} > 0$, then by the complementary slackness condition (equation (A.67)), we know that equation (A.35') holds as an equality. That is, we have:

$$\lambda_{NCi}\delta_N + \lambda_{PCi}\delta_P = C_{SM} + \lambda_{MSD} \qquad (i = 1, 2, 3). \qquad \text{(A.35'')}$$

Internal Land Values in the Base Case:

In the base case, there are assumed to be no restrictions on manure application, and thus, it can be applied in excess of the crop nutrient requirements. Furthermore, for comparison purposes, we assume that even in the base case farmers must dispose of all manure. Since the only cost is the cost of spreading, the least-cost way to dispose of any manure in excess of crop nutrient requirements is to spread it on cropland, even though the excess nutrients are assumed not to affect yields and the environmental consequences of doing so may be serious.[28]

Put differently, farmers in this base case are assumed to ignore the differential value of nutrients in the soil as reflected in the STP. For decision making purposes this is equivalent to assuming that the crop requirements for nitrogen are the same for requirements on high, medium, and low STP soils. Thus, for the base case, $\eta_{Ci} = \eta_C$ (for *i=1, 2, 3*). Phosphorus requirements are similarly assumed to be the same regardless of the STP (i.e., $\rho_{Ci} = \rho_C$ for *i=1, 2, 3*).

Based on this discussion, we can for the base case rewrite equations (A.33'') for land planted to corn as:[29]

[28] To implement this empirically, one need only specify equation (A.12) as an equality constraint and set the variable DM to zero, so off-farm disposal of manure is not an option

[29] By ignoring the STP, these three categories of cropland are indistinguishable from the farmer's decision making perspective. Therefore, from equations (A.31') and (A.29') and equation (A.33'') for all STP, we k now that $\lambda_{NC1} = \lambda_{NC2} = \lambda_{NC3} = \lambda_{NC}$ and $\lambda_{PC1} = \lambda_{PC2} = \lambda_{PC3} = \lambda_{PC}$ hold in this base scenario.

$\lambda_{Li} = \lambda_C Y_C - C_C - \lambda_{NC}\eta_C - \lambda_{PC}\rho_C$ (*i = 1, 2, 3*). (A.33'')

where λ_{L1}, λ_{L2} and λ_{L3} are the shadow prices of land on high, medium and low STP land, respectively. Thus, if STP and the restrictions it places on manure application of nutrients are ignored in the farmers' nutrient decisions, then, as one would expect, $\lambda_{L1} = \lambda_{L2} = \lambda_{L3}$, and the internal value of cropland in corn would be determined solely by the internal value of output less the internal value of all inputs other than land.

Internal Value of Land under the Policy Scenario with CAFO Restrictions on Nutrient Applications:

Under the proposed CAFO regulations nutrients from manure and commercial fertilizers can be applied to cropland only up to the P and N requirements as determined by the agronomic uptake levels for a given crop on a given soil. As shown in Figure 1, these restrictions are keyed to the STP.

To model this policy scenario, we must first let the variable DM, off-site manure disposal take on positive values (e.g. include it in the model). Next, we must modify the N and P input coefficients, $\eta_{Ci} and \rho_{Ci}$, in equations (A.33') from above, and reinterpret them slightly. In the base case, these coefficients represented the N and P inputs needed to raise corn. In this model, these coefficients are changed to reflect the amount of N and P by source (e.g. from manure or commercial fertilizer) that can be applied to corn. The difference between these allowable applications and the requirements are assumed to be equal to the crop uptake levels, and according to the STP these amounts of nutrients are inherent in the soil.

Since the over-application of manure is not allowed, manure is not spread on the high STP land, nor can there be any application of commercial P. Therefore, for high STP land (land class 1), we set $\rho_{C1} = 0$. Phosphorus can be applied up to the crop requirements on low STP soils (soil class 3), but only up to some fraction of this amount on medium STP soils (class 2 soils. Therefore, in equations (A.33') from above, we set $\rho_{C2} = \gamma_C \rho_{C3}$, where $0 < \gamma_C < 1$. Thus, we know that $\rho_{C3} > \rho_{C2}$.

As in the base case, we assume that the land classes are differentiated only by STP, so we again assume that the crop nitrogen requirements do not differ for high, medium and low STP soils (i.e., $\eta_{Ci} = \eta_C$ for *i=1,2,3*). Furthermore, although no manure or commercial P can be applied to high STP soils, commercial N can be applied up to the N requirements (assumed to be the crop removal rate). N can be applied up to this rate as well on medium STP land. All or part of this amount on medium STP land may come from manure, but the fraction coming from manure will be dictated by the ratio of allowable P to allowable N, ρ_{C2} / η_C, relative to their endogenously determined concentrations in the manure, δ_P / δ_N, from equations (A.8 and A.9). That is, if $\rho_{C2} / \eta_C < \delta_P / \delta_N$, then some of the N requirement must come from commercial N. Since manure can also be applied to low STP land, we know similarly that if $\rho_{C3} / \eta_C < \delta_P / \delta_N$ some of the N requirement must also come from commercial N.

From this discussion, we can re-write equations (A.33') to reflect these CAFO policy restrictions on nutrient application. They become:

$$\lambda_{L1} = \lambda_C Y_C - C_C - \lambda_{NC1}\eta_C \quad \text{(A1.33'')}$$
$$\lambda_{L2} = \lambda_C Y_C - C_C - \lambda_{NC2}\eta_C - \lambda_{PC2}\gamma_C \rho_{C3} \quad \text{(A2.33'')}$$
$$\lambda_{L3} = \lambda_C Y_C - C_C - \lambda_{NC3}\eta_C - \lambda_{PC3}\rho_{C3} \quad \text{(A3.33'')}$$

These terms λ_{L1}, λ_{L2} and λ_{L3} are the internal values or shadow prices of high, medium and low SPT land, respectively. And, in contrast to the base case above, it is evident that the internal value on land is in part determined by the nature of the CAFO restrictions on the application of nutrients. Unfortunately, without information on the internal values of nutrients applied to the different land classes (e.g. λ_{NCi} and λ_{PCi} for all *i*), we can say nothing about how these differential restrictions affect the relative magnitude of the shadow prices on high, medium and low STP soils.

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.[30] The implication of this assumption for the Kuhn-Tucker (first-order) conditions is that equation (A.31') holds with equality for the land with medium and low P soils.[31] Further, manure application on the medium and low P soils (and not on the high P land) allows for equation (A.31') to be re-written for land of soil test type *i* (for *i=1, 2, 3*) as:

$$\lambda_{NC1} \le \left[C_{SM} + \lambda_{MSD} - \lambda_{PC1}\delta_P\right]\cdot 1/\delta_N \quad \text{(A1.31'')}$$
$$\lambda_{NC2} = \left[C_{SM} + \lambda_{MSD} - \lambda_{PC2}\delta_P\right]\cdot 1/\delta_N \quad \text{(A2.31'')}$$
$$\lambda_{NC3} = \left[C_{SM} + \lambda_{MSD} - \lambda_{PC3}\delta_P\right]\cdot 1/\delta_N \quad \text{(A3.31'')}$$

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

[30] 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.

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

Substitute the expressions in equations (A2.31'') and (A3.31'') into the land value equations in (A2.33'') and (A233'') and recall the equality assumption on equation (A.31') 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 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 (A.37').

Equations (A1.33''), (A2.33'') and (A3.33'') can now be re-written as:

$$\lambda_{L1} = \lambda_C Y_C - C_C - \lambda_{NC1}\eta_C \quad \text{(A1.33''')}$$
$$\lambda_{L2} = \lambda_C Y_C - C_C - \left[C_{SM} - C_{DM} - \lambda_{PC}\delta_P\right]\cdot 1/\delta_N \cdot \eta_C - \lambda_{PC}\gamma_C\rho_{C3} \quad \text{(A2.33''')}$$
$$\lambda_{L3} = \lambda_C Y_C - C_C - \left[C_{SM} - C_{DM} - \lambda_{PC}\delta_P\right]\cdot 1/\delta_N \cdot \eta_C - \lambda_{PC}\rho_{C3} \quad \text{(A3.33''')}$$

where the sign on the off-site manure disposal cost variable, (e.g. C_{DM}) 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 these three equations are zero or negative (i.e., $-\left[C_{SM} - C_{DM} - \lambda_{PC}\delta_P\right] \leq 0$). This holds, for example, when the unit cost of spreading manure on farmland exceeds the off-site manure disposal cost. Then by equations (A1.33'''), (A2.33'''), and (A3.33'''). Recalling that ($\lambda_{NC1} \leq \left[C_{SM} + \lambda_{MSD} - \lambda_{PC1}\delta_P\right]\cdot 1/\delta_N$), it also holds that holds that: $\lambda_{L1} > \lambda_{L3}$. Thus, the shadow price on land in the high SPT category is higher than for land in the low STP category.

Next, assume that costs of off-site manure disposal rise so that the value of C_{DM} rises in the equations (A1.33'''), (A2.33'''), and (A3.33'''). The relevant expressions in -[ ] when multiplied outside by -1 can become positive (i.e., $-\left[C_{SM} - C_{DM} - \lambda_{PC}\delta_P\right] \geq 0$). Note that while this (now) positive term increases the overall value of λ_{Li} for the two lowest STP groups (*i=2, 3*),
For large enough increases in C_{DM}, the internal value of land in the low STP group could actually rise above the internal value for land in the highest STP group. Therefore, while high STP soils reduce production costs because of the inherent nutrient contents of the soil, these cost advantages in terms of lower nutrient costs can be outweighed by the value of land (over and above its value in crop production in the two lower STP because of their value as manure disposal sites.

To summarize this discussion, we know that when no policy is in effect, CAFO farm nutrient management on CAFOs is not likely to account for the inherent value of soil nutrients in the soil, as identified by a STP. Consequently, and for land of the same quality, the shadow prices for land are uniform regardless of the soil test P category to which the land belongs. With the new nutrient policy in effect, however, efforts to manage farm nutrients must recognize explicitly the value of soil nutrients in reducing the cost of production, but also the value of crop land as a repository of soil nutrients from animal waste. 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 the cost of off-farm disposal rises because, for example, of the distance to other farmland suitable for manure application, the internal value of a farmer's own land in the medium and low STP groups rises. 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. In Table A.8, we present several important sets of circumstances which help determine the relative shadow values of medium and low P soils for our stylized policy scenario and the critical values of the differences in the costs of manure application and off-site disposal at which the reversals in shadow land values occur.

Table A.1. Definitions of the Parameters and Variables in the Model

Parameters in the Model	Variables in the Model
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} = Cost per acre of corn on soil *i*, w/o fertilizers C_{Ai} = Cost per acre of alfalfa on soil *i*, w/ofertilizers 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* Y_{Ai} = Tons of alfalfa produced per acre of land *i* 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 = Lbs of N in manure from cow fed ration *j* P_j = Lbs of P in manure from cow fed ration *j* η_{Ci} = Lbs of N required per acre for corn on land *i* η_{Ai} =Lbs of N required per acre for alfalfa on land *i* ρ_{Ci} = Lbs of P required per acre for corn on land *i* ρ_{Ai} = Lbs of P required per acre for alfalfa on land *i*	X_j = Number of cows on ration *j* F = Tons of other feed purchased BN_{Ci} = Lbs of N purchased for corn on land *i* BN_{Ai} = Lbs of N purchased for alfalfa on land *i* BP_{Ci} = Lbs of N purchased for corn on land *i* BP_{Ai} = Lbs 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

Table A.2. A Proto-type Model

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

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

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

$$\begin{pmatrix} Xj, F, BN_{Ci}, BN_{Ai}, BP_{Ci}, BP_{Ai}, A_{Ci}, A_{Ai}, SM_{Ci}, SM_{Ai}, DM, \\ S_C, S_A, B_C, B_A, M, N_M, P_M \end{pmatrix} \geq 0 \quad j = 1, 2 \qquad \text{(A.1)}$$

such that:

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

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

Alfalfa in ration, production, selling, and buying:

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

Other feeds in ration, and buying:

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

Manure production:

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

N and P production in manure:

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

$$- P_1 X_1 - P_2 X_2 + P_M \leq 0 \qquad \text{(A.7)}$$

N and P application on corn:

$$\eta_{Ci} A_{Ci} - BN_{Ci} - \delta_N SM_{Ci} \leq 0; \text{ where } \delta_N = N_M / M \quad (i = 1, 2, 3) \qquad \text{(A.8)}$$

$$\rho_{Ci} A_{Ci} - BP_{Ci} - \delta_P SM_{Ci} \leq 0; \text{ where } \delta_P = P_M / M \quad (i = 1, 2, 3) \qquad \text{(A.9)}$$

N and P application on alfalfa:

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

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

Manure inventory:

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

Land:

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

Dairy cow Inventory:

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

Table A.3. The Lagrangian Function

$$L = [\ \sum_{j=1}^{2}\left(P_W Y_{Xj} - C_{Xj}\right)X_j - C_F F - C_N \left[\sum_{i=1}^{3} BN_{Ci} + \sum_{i=1}^{3} BN_{Ai}\right]$$
$$- C_P \left[\sum_{i=1}^{3} BP_{Ci} + \sum_{i=1}^{3} BP_{Ai}\right] - \sum_{i=1}^{3} C_{Ci} A_{Ci} - \sum_{i=1}^{3} C_{Ai} A_{Ai}$$
$$- C_{SM}\left[\sum_{i=1}^{3} SM_{Ci} - \sum_{i=1}^{3} SM_{Ai}\right] - C_{DM} DM + P_C S_C + P_A S_A$$
$$- \tilde{C}_C B_C - \tilde{C}_A B_A\ \ ] + \lambda_C \left[0 - \left(a_{C1} X_1 + a_{C2} X_2 - \sum_{i=1}^{3} Y_{Ci} A_{Ci} + S_C - B_C\right)\right]$$
$$+ \lambda_A \left[0 - \left(a_{A1} X_1 + a_{A2} X_2 - \sum_{i=1}^{3} Y_{Ai} A_{Ai} + S_A - B_A\right)\right] + \lambda_F \left[F - \left(a_{F1} X_1 + a_{F2} X_2\right)\right]$$
$$+ \lambda_M \left[0 - \left(-M_1 X_1 - M_2 X_2 + M\right)\right] + \lambda_{NM}\left[0 - \left(-N_1 X_1 - N_2 X_2 + N_M\right)\right]$$
$$+ \lambda_{PM}\left[0 - \left(-P_1 X_1 - P_2 X_2 + P_M\right)\right] + \lambda_{NCi}\left[0 - \left(\eta_{Ci} A_{Ci} - BN_{Ci} - \delta_N \cdot SM_{Ci}\right)\right]$$
$$+ \lambda_{PCi}\left[0 - \left(\rho_{Ci} A_{Ci} - BP_{Ci} - \delta_P \cdot SM_{Ci}\right)\right] + \lambda_{NAi}\left[0 - \left(\eta_{Ai} A_{Ai} - BN_{Ai} - \delta_N \cdot SM_{Ai}\right)\right]$$
$$+ \lambda_{PAi}\left[0 - \left(\rho_{Ai} A_{Ai} - BP_{Ai} - \delta_P \cdot SM_{Ai}\right)\right]$$
$$+ \lambda_{MSD}\left[0 - \left(\sum_{i=1}^{3} SM_{Ci} + \sum_{i=1}^{3} SM_{Ai} + DM - M\right)\right] + \lambda_{Li}\left[L_i - \left(A_{Ai} + A_{Ai}\right)\right]$$
$$+ \lambda_H \left[H - \left(X_1 + X_2\right)\right] \qquad \text{(A.15)}$$

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

$$L_\nu \le 0;\ L\lambda \ge 0 \qquad \text{(A.16)}$$

$$\nu \cdot L_\nu = 0;\ \lambda \cdot L\lambda = 0 \qquad \text{(A.17)}$$

$$\nu \ge 0;\ \lambda \ge 0 \qquad \text{(A.18)}$$

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

ν = Variable

λ = Lagrangian multiplier associated with constraint

Table A.4. The first order conditions I: $L_v \le 0$

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

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

$$L_F : -C_F + \lambda_F \le 0 \qquad \text{(A.21)}$$

$$L_{SC} : P_{SC} - \lambda_C \le 0 \qquad \text{(A.22)}$$

$$L_{SA} : P_{SA} - \lambda_A \le 0 \qquad \text{(A.23)}$$

$$L_{BC} : -\tilde{C}_C + \lambda_C \le 0 \qquad \text{(A.24)}$$

$$L_{BA} : -\tilde{C}_A + \lambda_A \le 0 \qquad \text{(A.25)}$$

$$L_M : -\lambda_M - \sum_{i=1}^{3} \lambda_{NAi} \cdot N_M \cdot M^{-2} \cdot SM_{Ai} - \sum_{i=1}^{3} \lambda_{PAi} \cdot P_M \cdot M^{-2} \cdot SM_{Ai} - \sum_{i=1}^{3} \lambda_{NCi} \cdot N_M \cdot M^{-2} \cdot SM_{Ci} - \sum_{i=1}^{3} \lambda_{PCi} \cdot P_M \cdot M^{-2} \cdot SM_{Ci} \le 0 \qquad \text{(A.26)}$$

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

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

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

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

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

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

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

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

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

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

$$L_{DM} : -C_{DM} - \lambda_{MSD} \le 0 \qquad \text{(A.37)}$$

Table A.5. The first order conditions II: $L_\lambda \geq 0$		
$L_{\lambda C}: \sum_{i=1}^{3} Y_{Ci} A_{Ci} \geq a_{C1} X_1 + a_{C2} X_2 + S_C$		(A.38)
$L_{\lambda A}: \sum_{i=1}^{3} Y_{Ai} A_{Ai} \geq a_{A1} X_1 + a_{A2} X_2 + S_A$		(A.39)
$L_{\lambda F}: F \geq a_{F1} X_1 + a_{F2} X_2$		(A.40)
$L_{\lambda M}: M \geq M_1 X_1 + M_2 X_2$		(A.41)
$L_{\lambda NM}: N_1 X_1 + N_2 X_2 \geq N_M$		(A.42)
$L_{\lambda PM}: P_1 X_1 + P_2 X_2 \geq P_M$		(A.43)
$L_{\lambda NCi}: \sigma_N SM_{Ci} + BN_{Ci} \geq \eta_{NCi} A_{Ci}$	(i=1, 2, 3)	(A.44)
$L_{\lambda NAi}: \sigma_N SM_{Ai} + BN_{Ai} \geq \eta_{NAi} A_{Ai}$	(i=1, 2, 3)	(A.45)
$L_{\lambda PCi}: \sigma_P SM_{Ci} + BP_{Ci} \geq \eta_{PCi} A_{Ci}$	(i=1, 2, 3)	(A.46)
$L_{\lambda PAi}: \sigma_P SM_{Ai} + BP_{Ai} \geq \eta_{PAi} A_{Ai}$	(i=1, 2, 3)	(A.47)
$L_{\lambda MSD}: M \geq \sum_{i=1}^{3} SM_{Ci} + \sum SM_{Ai} + DM$		(I.48)
$L_{\lambda Li}: L_i \geq A_{Ci} + A_{Ai}$	(A=1, 2, 3)	(I.49)
$L_{\lambda H}: H \geq X_1 + X_2$		(A.50)

Table A.6 The first order conditions III (complementary slackness): $\nu \cdot L_X = 0$; $\nu \geq 0$ for all ν

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

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

$$F \cdot L_F : F\left[-C_F + \lambda_F\right] = 0 \quad \text{(A.53)}$$

$$S_C \cdot L_{SC} : S_C\left[P_{SC} - \lambda_C\right] = 0 \quad \text{(A.54)}$$

$$S_A \cdot L_{SA} : S_A\left[P_{SA} - \lambda_A\right] = 0 \quad \text{(A.55)}$$

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

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

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

$$N_M \cdot L_{NM} : N_M\Big[-\lambda_{NM} + \sum_{i=1}^{3}\lambda_{NCi} \cdot 1/M \cdot SM_{Ci} + \sum_{i=1}^{3}\lambda_{NAi} \cdot 1/M \cdot SM_{Ai} \Big] = 0 \quad \text{(A.59)}$$

$$P_M \cdot L_{PM} : P_M\Big[-\lambda_{PM} + \sum_{i=1}^{3}\lambda_{PCi} \cdot 1/M \cdot SM_{Ci} + \sum_{i=1}^{3}\lambda_{PAi} \cdot 1/M \cdot SM_{Ai} \Big] = 0 \quad \text{(A.60)}$$

$$BN_{Ci} \cdot L_{BNCi} : BN_{Ci}\left[-C_N + \lambda_{NCi}\right] = 0 \qquad (i = 1, 2, 3) \quad \text{(A.61)}$$

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

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

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

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

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

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

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

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

Table A.7. The first order conditions IV (complementary slackness): $\lambda \cdot L\lambda = 0$; $\lambda \geq 0$ for all λ

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

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

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

$$\lambda_M \cdot L_{\lambda M} : \left[M_1 X_1 + M_2 X_2 - M\right] \quad \text{(A.73)}$$

$$\lambda_{NM} \cdot L_{\lambda NM} : \lambda_{NM} \left[N_1 X_1 + N_2 X_2 - N_M\right] \quad \text{(A.74)}$$

$$\lambda_{PM} \cdot L_{\lambda PM} : \lambda_{PM} \left[P_1 X_1 + P_2 X_2 - P_M\right] \quad \text{(A.75)}$$

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

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

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

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

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

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

Table A.8: Relative magnitudes for shadow values for cropland with different STPs and 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.

Appendix B
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.

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.

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 loadings. 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).

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).

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.[32] 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:

$$ROP_{man} = 0.4 * PR_{man} * PDF_{man} * \left(RO/PPT\right) \qquad \text{(B.1)}$$

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 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 feed 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:

$$PDF_{man} = \left(RO/PPT\right)^{0.225} \qquad \text{(B.2)}$$

[32] 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 PDF_{man} is the manure distribution factor and *RO* and *PPT* are the runoff and precipitation variables, respectively, as defined above in equation (B.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 is determined by:

$$RO = (PPT - 0.2 \cdot S)^2 / (PPT + 0.8 \cdot S) \qquad \text{(B.3)}$$

where *RO* is the depth of runoff (in.) from the corn fields 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.) of effective available storage on the fields.

Further, *S* is determined by:

$$S = (1000/CN) - 10 \qquad \text{(B.4)}$$

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 (B.1) through (B.4), with some modifications. Estimates of the amount of dissolved P in runoff from applied fertilizers are given by:

$$ROP_{fer} = PR_{fer} * PDF_{fer} * (RO/PPT) \qquad \text{(B.5)}$$

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 by:

$$PDF_{fer} = 0.034 * \exp[3.4 * (RO/PPT)] \qquad \text{(B.6)}$$

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 (B.3).

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 (B.1) through (B.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 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 (B.1) and (B.5) can be re-written as:

$$ROP^{t}_{man} = 0.4 * (PR^{t}_{man} - PR^{t-1}_{man}) * PDF_{man} * (RO/PPT) \qquad \text{(B.7)}$$

$$ROP^{t}_{fer} = (PR^{t}_{fer} - PR^{t-1}_{fer}) * PDF_{fer} * (RO/PPT) \qquad \text{(B.8)}$$

where ROP_{man}, ROP_{fer}, PR_{man}, PR_{fer}, PDF_{man}, PDF_{fer}, *RO* and *PPT* are defined as in equations (B.1) through (B.6). 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 events within the year or season as:

$$PRO_{j} = \sum_{t=1}^{3} ROP^{tj}_{man} + \sum_{t=1}^{3} ROP^{tj}_{fer} \qquad j = 1,\ldots, J \qquad \text{(B.9)}$$

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:

$$TPRO = \sum_{j=1}^{J} \left(PRO_j * Ac_j \right) \qquad \text{(B.10)}$$

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

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