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ESSAYS ON NUTRIENT MANAGEMENT RISK IN LIVESTOCK PRODUCTION: CITIZEN ENVIRONMENTAL COMPLAINTS, MANURE HAULING SYSTEM COSTS, AND ANIMAL EMISSION TAXES

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JOLEEN CHRISTINE HADRICH

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By

Joleen Christine Hadrich

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ABSTRACT

ESSAYS ON NUTRIENT MANAGEMENT RISK IN LIVESTOCK PRODUCTION: CITIZEN ENVIRONMENTAL COMPLAINTS, MANURE HAULING SYSTEM COSTS, AND ANIMAL EMISSION TAXES

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Nutrient management on livestock operations must be environmentally friendly, labor efficient, and cost effective. Poor nutrient management practices may lead to potential citizen complaints resulting in mitigation costs, fines or lawsuits. An econometric analysis of citizen complaints regarding surface water, groundwater, and odor concerns was completed to analyze farm characteristics affecting the probability of a verified citizen complaint. Farm compliance with environmental regulations involves policy uncertainty and sunk cost investments. A spreadsheet-based manure transport and land application decision tool, MANURE$HAUL, was developed to provide farmers, custom applicators, and others involved with the manure management a manure hauling capacity, time and cost calculator for liquid manure hauling systems using tractor-drawn tank spreaders and truck-drawn nurse tanks used in parallel with tractor-drawn tank spreaders. An optimal control theory model was used to model the uncertainty regarding the size of an animal air emission tax and its effects on a farmer's investment in emission-reducing technology.

To Mom, Dad, Dean, Daryl, Joelle, and Joylynn. Thanks for supporting me.

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CHAPTER 1: GENERAL INTRODUCTION

Animal production levels and average herd sizes have been trending upwards on US agricultural farms for decades. Manure hauling systems must accommodate the ever increasing volume of manure while considering more stringent environmental regulations. Poor nutrient management practices could lead to manure leaks, spills, and run-off from field application or manure storage resulting in fines or lawsuits. In addition to managing the farming operation, farmers must also address increased public scrutiny regarding farming practices with urban areas expanding closer and closer to rural agricultural settings. In order to remain profitable agricultural producers must be cognizant of these challenges and their implications on future management decisions.

In response to the increased interaction between the urban areas and production agriculture, past legislation regarding environmental pollution from non-point pollution sources, such as the 1972 Clean Water Act and 1990 Clean Air Act, many states have created "Right to Farm" Programs. These programs provide legal protection for livestock producers against nuisance lawsuits and citizen complaints while also providing a set of accepted management practices to be in compliance with environmental guidelines. Nutrient management practices vary by state but provide an environmental compliance benchmark for livestock producers. In Michigan, the Right to Farm program was initiated in 1981 which developed a set of Generally Accepted Agricultural Management Practices (GAAMPs). This program is voluntary, but participating in the program provides producers with a form of legal protection against nuisance lawsuits and citizen complaints which may outweigh the potential future costs of fines and legal actions if the farm is not in compliance with current environmental regulations.

Environmental regulations continue to evolve over time with knowledge gained through research and evaluating the end result of current situations. Many times these updates and changes in environmental regulations cause livestock producers to delay investment in potential abatement technology in fear that it may be outdated before the useful life of the equipment has expired. This uncertainty must be accounted for when assessing the potentially large capital investments made by farmers in abatement technology.

Manure nutrient management considering environmental regulations requires an understanding of the manure hauling system components and its associated costs. Choosing a less than optimal manure hauling system may increase manure hauling time and cause potential delays in crop tillage and planting. Therefore, individual farms must consider each of these components for their farm before making potential capital investments in manure hauling systems. Current options in manure hauling systems vary greatly in labor, machinery requirements, ownership and operating costs, and compatibility with environmental regulations.

In addition to manure nutrient management, agricultural producers are facing increased public scrutiny for animal air emissions (ammonia (NH_3), methane, and particulate matter) from their farm. Odor management is an area of growing concern for agricultural producers. While odor is not regulated in 2009, per se, agricultural producers must be vigilant in adopting practices to limit odor from their farm in an attempt to decrease future citizen complaints and be pro-active about potential future air emission regulations. Examples of air emission reduction practices include incorporating manure into the soil immediately after application, injecting manure, or building a long-term manure storage facility with appropriate abatement technology to limit air emissions (manures storage covers, biofilters, etc.).

This dissertation consists of three essays which each address particular elements of nutrient management risk on livestock operations in Michigan. The first essay provides an understanding of the interaction between production agriculture and urban areas through an analysis of Right to Farm program citizen complaints regarding surface water, groundwater, and odor concerns. Environmental citizen complaint data was collected and used to determine farm and county level factors influencing the probability of a verified environmental citizen complaint issued against livestock producers in Michigan. Costs of implementing corrective practices required to mitigate a verified citizen complaint were estimated which were used in a two-stage Heckman procedure to determine the individual farm characteristics influencing the cost of the corrective practices required to mitigate environmental citizen complaints. The second essay develops an excel spreadsheet-based manure transport and land application decision tool, MANURE$HAUL, to evaluate comparisons of cost-effective alternative manure hauling systems. MANURE$HAUL provides an accurate estimate of time needed for manure pumping, transport, and land application as a function of hauling distance, spreader capacity, manure equipment cost, labor, and the nutrient value of manure. The final essay considers the investment policy in air-emission abatement for uncertain environmental taxes on animal air emissions. An optimal control theory model is used to model the uncertainty regarding the size of the emission tax and its effect on a farmer's investment policy.

CHAPTER 2: CITIZEN COMPLAINTS AND ENVIRONMENTAL COMPLIANCE ON MICHIGAN LIVESTOCK OPERATIONS

2.1 Introduction

Interaction between urban areas and production agriculture often results in citizen complaints regarding manure management, air quality, and water quality concerns. Recognizing that livestock operations must be able to collect and dispose of manure while being sensitive to environmental consequences, the 1981 Michigan Right to Farm Act defined a set of generally accepted manure management practices (GAAMP) that, if followed, ensure farm protection from nuisance complaints and lawsuits (Michigan Department of Agriculture 2008b). The GAAMP standards are reviewed and updated annually to address current environmental concerns by a committee of industry, state and university personnel. A response program was initiated in 1986 to address citizen environmental complaints received by the Michigan Department of Agriculture (MDA), Right to Farm Program (Michigan Department of Agriculture 2008b). When an environmental complaint is filed against a farm an inspection is scheduled within seven business days. Common examples of potential GAAMP standard violations evaluated during inspections include livestock in streams and rivers, surface applied manure not incorporated within forty-eight hours of application, and manure application on frozen or snow-covered soil.

Following an initial inspection each complaint is categorized as non-verified, verified, or transferred to an enforcement agency. If an inspected farm is complying with all relevant GAAMP standards, the complaint is classified as non-verified by the Right to Farm inspector. While non-verified complaints may have been caused by practices or events that legitimately irritated the complainant, they were determined to require no corrective action and, thus, do not require mitigation or otherwise alter producer behavior. If the inspected farm is out of compliance, the complaint is classified as verified. Farms with verified complaints must correct the environmental issue on their farm in a timely manner to regain Right to Farm protection. Progress towards completion of corrective practices is assessed by follow-up inspections. Should the farm fail to make adequate progress to correct environmental concerns, the Right to Farm inspector may close the case leaving no protection or forward the case to the Michigan Department of Environmental Quality for enforcement. In situations where the original complaint violation is not under Michigan Department of Agriculture jurisdiction, such as a direct manure discharge into public waters, the complaint is transferred to the Michigan Department of Environmental Quality for enforcement action. This distinction of complaint classification allows for an examination of the factors related to complaint status.

Past research has recognized the importance of relationships between environmental regulations and citizen complaints (Cohen; Eckert; Helland; and Heyes). Few studies have evaluated the effects of citizen complaints and consequences on behavior. Dasgupta and Wheeler assessed factors affecting citizen environmental complaints using Chinese provincial data and determined that complaints provided useful information but consumed a large share of inspection resources making them relatively costly. Huang and Miller evaluated the relationship between citizen complaints, swine production, and county characteristics using swine farm inspection data for Illinois. They concluded that citizen issued complaints were a more efficient source of monitoring information than regularly scheduled inspections. Huang and Miller also found that building type and swine production intensity were the factors that most influenced the probability of a regulatory violation.

Citizen complaints are potentially a source of low-cost monitoring of environmental violations (Huang and Miller; Dasgupta and Wheeler). Neighbors and passersby observe livestock facilities on a daily basis and may witness environmental issues, whereas regulatory agencies usually do not have the resources to monitor a large number of farms on a regular basis. On the other hand, complainants may not be able to identify legitimate environmental concerns as opposed to acceptable management practices. In some cases, individuals or groups may have a high propensity to complain. These instances often occur in areas where there are concentrated animal feeding operations (CAFOs) located near the rural-urban fringe. With little basis to evaluate practices used on the farm, complaints instead may be filed because that person or group disapproves of the location, size, or production practices of the farm particularly as these relate to odor.[1] This research examines how individual farm production and county level characteristics influence the probability of a verified complaint. We also examine the interdependence between farm production characteristics and costs associated with corrective practices required to mitigate verified complaints.

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[1] Odor is not regulated in Michigan (or in most other states). However, the underlying issue(s) causing odor may be regulated. Air quality issues are typically handled through corrective measures such as incorporating manure into soil within forty-eight hours of application, limiting manure application on the weekends, or developing a manure management system plan in accordance with Michigan GAAMP standards.

2.2 Data

Environmental citizen complaint data were collected from the Michigan Department of Agriculture for the period from October 1998 through December 2007. The reports detailed individual characteristics of the farm inspected including: zip code and county of both complainant and livestock operation, type of livestock enterprise, herd size in animal units (AU), type of manure storage, current manure analysis, soil tests, existence of comprehensive nutrient management plan (CNMP) or manure management system plan (MMSP) and whether either plan was under development or updating, manure incorporation, corrective practices implemented to respond to verified complaints, and days required to implement corrective practices.[2]

Environmental citizen complaints were categorized as relating to air, ground water, surface water, combination, or "other" complaints which include flies, dust, and pro-active complaints. Pro-active complaints were those requested by the farmer to ensure GAAMP standards were followed. Over the approximately ten year period examined, the most common complaint types were air and surface water which together accounted for 75% of all complaints (Figure 2a). Ground water, combination, and other complaints were less common. Dairy producers (32%), beef producers (16%), and horse

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[2] An "animal unit" is a metric of manure generation used to assess the size of operations across animal species. One animal unit was defined as: one feeder calf, heifer, or steer; 0.7 mature dairy cows (whether a milking or dry cow); 25 pigs weighing over 55 pounds; 0.5 horses; 10 sheep or lambs; 55 turkeys; 100 laying hens or broilers when the facility has unlimited continuous flow watering systems; 30 laying hens or broilers when facility has liquid manure handling system (MDA, 2008b).

facilities (16%) received the largest share of complaints.[3] Similarly dairy, beef, and equine enterprises were the focus of the majority of surface water complaints while dairy and swine operations received the largest number of odor complaints.

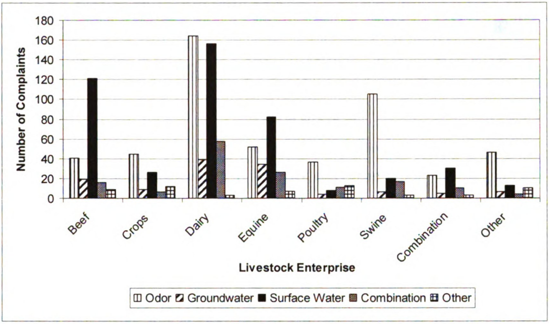

Figure 2a. Complaint type by livestock enterprise

By complaint status 45% were classified as non-verified and 55% were classified as verified (including enforcement level complaints). Figure 2b. presents the number of complaints by complaint status classification and livestock enterprise. Dairy, beef and equine farms received more verified complaints whereas as the opposite held for poultry and swine farms.

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[3] The remaining livestock enterprises included poultry, swine, crops, combination livestock, and other livestock. Crops referred to fertilizer practices, soil erosion, and crop production practices. Other livestock include goats, sheep, deer, elk, bees, and by-product utilization.

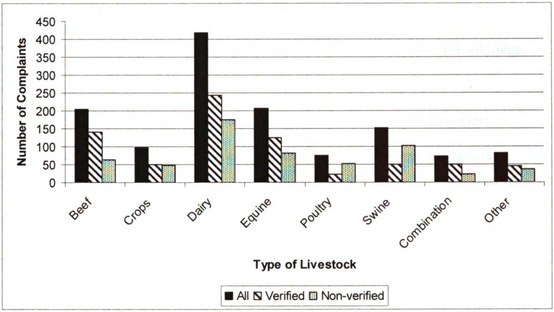

Figure 2b. Complaint classification by livestock enterprise

2.3 Verified Citizen Complaints

In order to understand the factors affecting the likelihood that a complaint was verified, we used a probit model to estimate probability of a verified complaint as defined by complaint type, farm characteristics, county characteristics, and seasonal factors. Using this model, the probability of a verified complaint can be expressed as:

$$Y_l^* = X\eta + e_l \qquad (1)$$

$$Y_l^* = \begin{cases} 1, & \textit{if verified} \\ 0, & \textit{if nonverified} \end{cases}$$

where Y_l is the a binary variable equal to one for verified complaints and zero for non-verified complaints, **X** denotes an array of variables that are hypothesized to affect the probability of a verified complaint, η is a vector of parameters, e_l is the error term, and l

indexes farm. We assumed that e_l was normally distributed which allowed us to estimate a probit model from equation (1) using maximum likelihood techniques (Wooldridge, 2003).

Explanatory variables for the analysis were divided into four categories: complaint type, farm characteristics, county characteristics, and seasonal factors. Summary statistics of the explanatory variables are presented in Table 2a. Complaint type significance is likely to be related to how recognizable the potential violation is to a typical citizen. For example, surface water related complaints may be more likely to be visible concerns such as waste run-off.

Farm characteristics included livestock enterprise, manure handling system, animal units, and distance between complainant and farm. Livestock enterprise types were beef, crops, dairy, equine, poultry, swine, a combination of two or more groups, and "other" livestock. Crop complaints referred to fertilizer practices, soil erosion, and crop production practices. The "other" livestock category included complaints concerning by-products from fruit and vegetable processing, sheep, goats, deer, and elk.

Manure storage was categorized into three groups. No storage meant the farm did not have manure storage requiring, in the case of dairy farms, hauling manure on a daily basis. Short-term storage was defined as manure storage for less than six months and included stockpiling on dirt and cement as well as manure stored in barns and lots. Long-term manure storage was defined as adequate for six months or more. Earthen and concrete manure pits as well as composting were examples of long-term storage for beef, dairy, swine, and poultry operations. Long-term manure storage for equine operations included stockpiling of manure. A manure storage structure is not required for equine

Table 2a. Definition and Summary Statistics of Explanatory Variables, All Complaints

Variable	Obs.	Mean Value	Std Dev.	Definition
Dependent Variable				
Verified Complaint	1307	0.554	--	Verified complaint (0/1)
Complaint Type				
Odor	1297	0.396	--	Odor complaint (0/1)
Groundwater	1297	0.094	--	Groundwater complaint (0/1)
Surface water	1297	0.352	--	Surface water complaint (0/1)
Combination complaint	1297	0.113	--	More than one environmental concern issued in the complaint (0/1)
Other complaint	1297	0.045	--	Other complaints-flies, noise, dust (0/1)
Farm Characteristics				
Distance	1310	0.498	--	Zip code between complainant and farm is different (0/1)
AU	1097	548.4	1182	Animal units on farm (AU)
Days	646	172.4	167	Days used to implement corrective practices
Manure Storage				
No storage	1029	0.080	--	No manure storage (0/1)
Short-term	1029	0.245	--	Short-term manure storage (0/1)
Long-term	1029	0.490	--	Long-term manure storage (0/1)
Livestock Enterprise				
Beef	1310	0.157	--	Beef cattle (0/1)
Dairy	1310	0.320	--	Dairy cattle (0/1)
Swine	1310	0.116	--	Swine (0/1)
Equine	1310	0.158	--	Equine (0/1)
Poultry	1310	0.057	--	Poultry (0/1)
Crop	1310	0.075	--	Crops (0/1)
Other Livestock	1310	0.062	--	Goat, sheep, other livestock types (0/1)
Combination Livestock	1310	0.055	--	More than one livestock type (0/1)
Seasonal factors				
Spring	1310	0.340	--	Complaint issued in April, May, June (0/1)
Summer	1310	0.309	--	Complaint issued July, August, September (0/1)
Fall	1310	0.175	--	Complaint issued in Oct., Nov., Dec. (0/1)
Winter	1310	0.175	--	Complaint issued in Jan., Feb., March (0/1)
Year	1310	2003	2.6	Time trend (years)
County Characteristics				
AU density	1309	42.3	36.9	County animal unit density (au/mile^2)
Population density	1309	227.9	307	County population density (pop/mile^2)
Farms (county)	1309	1026	355	Number of farms in the county
Median household Income	1309	42395	7212	County level median household income ($)
HS education	1309	83.5	3.6	County level residents with high school diploma or higher (%)

facilities under GAAMP standards due to low nutrient content and amount of manure produced.

Distance between complainant and farm was represented by a dummy variable coded as one for those complainants that resided at a different zip code than the farm in question. The null hypothesis was that complaints from other zip codes would be more likely verified as those complainants would be less likely bothered by nuisance issues.

County characteristics included animal unit density and number of farms (United States Department of Agriculture, 2007), median household income (Michigan Information Center), and percent of population with high school education level or higher (United States Census Bureau). County level animal density and number of farms in the county captured farming intensity. It was hypothesized that higher county animal unit densities were more likely to have verified complaints due to a higher proportion of farmers and familiarity with agriculture. County level education and income variables were included to capture the characteristics of communities around and near the farm. Seasonal factors were addressed using dummy variables. Complaint year was also included.

Table 2b presents regression results for the probability that a filed complaint was verified. The omitted base set of characteristics for the categorical variables were an odor complaint filed against a dairy operation with long-term storage in the Spring season. This base case represented the most common type of complaint, operation, manure storage, and season. Results revealed that the probability of a verified complaint was affected by complaint type. Surface water and combination complaints were 18 and 16% more likely to be verified relative to odor complaints, respectively. A combination

Table 2b. Probability of a Verified Complaint

Variable	Coefficient	Standard Error	Marginal effects
Complaint Type [1]			
Groundwater	-0.0065	(0.1632)	-0.0025
Surface water	0.4766	(0.1231)***	0.1757
Combination complaint	0.4552	(0.1531)***	0.1615
Other complaint	-0.3883	(0.2398)	-0.1528
Farm Characteristics			
AU	-0.0002	(0.0001)***	-0.0001
Distance	0.1767	(0.1009)*	0.0672
Manure Storage [2]			
No Storage	0.1666	(0.1766)	0.0621
Short-term	-0.0466	(0.1389)	-0.0178
Livestock Enterprise [3]			
Beef	0.1180	(0.1638)	0.0444
Swine	-0.5166	(0.1622)***	-0.2028
Equine	-0.1932	(0.1520)	-0.0748
Poultry	-0.6926	(0.2796)***	-0.2708
Crop	-0.3366	(0.2660)	-0.1322
Other livestock	-0.2119	(0.2252)	-0.0826
Combination livestock	0.0079	(0.2089)	0.0030
Seasonal factors [4]			
Summer	0.0223	(0.1160)	0.0085
Fall	-0.4306	(0.1335)***	-0.1684
Winter	0.2032	(0.1369)	0.0758
Year	-0.0239	(0.0202)	-0.0091
County Characteristics			
AU density	-0.0011	(0.0015)	-0.0004
Population density	0.0003	(0.0002)	0.0001
Farms (county)	0.0001	(0.0002)	4.33E-05
Median household income	9.16E-06	(1.04E-05)	3.49E-06
HS education	-0.0489	(0.0184)***	-0.0186
Constant	51.7860	(40.5349)	
Chi-square	138.96		
Probability>Chi-square	0.000		
Log-likelihood	-511.15		
Pseudo R-square	0.1197		
Predicted probability at mean	0.6174		
Sample size	867		

[1] Base complaint type = odor

[2] Base livestock type = dairy

[3] Base manure storage type = long-term

[4] Base season = spring

*** Significant at 1% level

** Significant at 5% level

* Significant at 10% level

complaint addressed more than one issue on a farm, for example odor and surface water concerns. Thus, the complaint types that could be visually observed in the form of, for example, manure run-off were more likely to be verified than odor complaints. We suspect that most Michigan citizens were unaware that there were no explicit odor regulations pertaining to livestock operations.

Complaints issued against swine and poultry operations had a 20 and 27% lower probability of a verified complaint relative to dairy operations, respectively. This may be related to odor as confinement swine and poultry operations following standard practices often produce odor that people find more objectionable than cattle or horse operations. Thus, even though type of complaint is controlled for and odor itself is not regulated, the objectionable odor from swine and poultry farms may contribute to a higher level of nuisance complaints.

The probability of a verified complaint was not dependent on manure storage type. We found this result surprising given the focus on avoiding manure spreading on frozen ground in Michigan (Michigan Department of Agriculture, 2008b). With many operations lacking long-term storage, we expected more verified complaints would be associated with short-term storage.

Animal units (AU) present on farm, which measures herd size, was found to be negative and significant. As the number of animals units increased, probability of a verified complaint declined. This may be surprising since large animal operations seem to be the focus of many environmentally related controversies. However, large operations are often newer facilities with modern manure handling technologies which have completed thorough and intensive site selection review. Site selection involves an extensive inspection of buildings and waste storage facilities on a farm and practices used in order for the farm to be incompliance with GAAMP standards for their day-to-day farming operations (Michigan Department of Agriculture, 2008a). These results suggest that large operations were significantly more likely to receive non-verified nuisance complaints perhaps in part caused by perceptions and press related to operation size and production practices. This indicates a need for confined animal feeding operations to be pro-active in public and neighbor relations that past research has found to produce positive results with respect to complaints (Hadley, Harsh and Wolf).

The probability of a verified complaint increased by 7% when the complainant and farm were not located in the same zip code. This may indicate that people passing by are more likely to call only when noticing a potentially serious violation. It may also indicate the effect of citizen groups who actively and aggressively monitor large livestock operations in some parts of Michigan (Sierra Club; Environmentally Concerned Citizens of South Central Michigan). Finally, it may indicate a hesitation on the part of neighbors to report others in close proximity with whom they are likely to have future interaction.

A complaint issued in the Fall had a decreased probability of verification relative to Spring complaints. People tend to be more active during the Spring creating opportunities for complaints. During Fall months farmers are harvesting crops and often incorporating manure shortly after harvest, a practice which would decrease the likelihood of a verified complaint.

The negative and significant marginal effect for the percent of the county population with a high school level education or higher indicated that more educated people were less likely to make verified complaints. Population density, the number of farms, AU density, and median household income at the county level did not significantly influence the probability of verified complaints.

2.4 Corrective practices implemented

For verified complaints, mitigating practices aligned with the GAAMP standards were required. Corrective practices included developing a manure management system plan (MMSP) or a more formal comprehensive nutrient management plan (CNMP), soil analysis, manure analysis, incorporating applied manure, manure stockpile utilization, installing stream bank fencing, and controlling waste run-off. Completing and filing an MMSP or CNMP entails submitting an official document outlining manure production, utilization, and application on the farm.[4] Manure stockpile utilization required the farm to remove manure stockpiles either through manure application or disposal through other arrangements, such as potentially giving it away to neighboring farms. Installing stream bank fencing included controlling water access for livestock near lakes, rivers, and streams. Controlling waste run-off required the farmer to install appropriate waste storage for manure as well as milk waste water for dairy operations.

Table 2c displays the corrective practices implemented to mitigate verified complaints across livestock enterprises. Dairy and swine operations were most often required to develop a MMSP whereas equine and “other” livestock operations were frequently required to remove stockpiled manure. “Other” livestock groups were typically small farms (less than 10 acres) with goats or sheep who typically did not have a

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[4] A MMSP must be filed with the Right to Farm Program for AFOs. Soil and manure analysis are needed as well as a formal document outlining manure management. CNMP are a requirement for the National Pollution Discharge Elimination System for CAFOs. CNMP must be certified whereas MMSP do not require certification.

Table 2c. Corrective Practices to Mitigate Verified Complaints

Corrective Practice	Beef	Crops	Dairy	Equine	Poultry	Swine	Comb.[1]	Other
	Percent (%)							
Soil analysis	11.54	37.21	14.22	17.86	31.82	22.92	0.00	30.30
MMSP	19.23	4.65	47.25	18.75	31.82	43.75	28.57	9.09
CNMP	0.77	2.33	3.21	0.89	9.09	4.17	2.38	0.00
Manure incorporation	2.31	6.98	14.68	4.46	13.64	18.75	4.76	12.12
Stockpile utilization	4.62	13.95	1.38	22.32	9.09	0.00	16.67	39.39
Stream bank fencing	53.08	0.00	10.09	16.07	0.00	4.17	30.95	3.03
Vegetative buffer	3.85	32.56	1.83	13.39	0.00	2.08	9.52	3.03
Control run-off structure	4.62	2.33	7.34	6.25	4.55	4.17	7.14	3.03

[1] Comb.=Combination livestock

large land base on which to dispose of manure. In Michigan, beef cow and feeder operations typically use a pasture-based system. Over fifty percent of beef operations with verified complaints were required to install stream bank fencing indicating Michigan's increased efforts to exclude livestock from waterways. Cropping operations were most commonly required to provide soil analysis and install vegetative buffers to prevent waste run-off.

A second objective was to understand how farm characteristics influenced cost of implementing corrective practices required to abate environmental problems on farms receiving a verified complaint. While the costs to mitigate complaints were not collected, we were able to estimate mitigation costs for each operation using farm and complaint information. A manure management plan was assumed to cost \$1,498 per farm under 1,000 animal units (AFO) and \$3,382 per farm with more than 1,000 animal units (CAFO) (Vollmer-Sanders, Batie, and Wolf). Soil samples cost \$15 per sample with one sample taken for every five acres (Bundy et al.). Manure analysis cost $25 per sample (Michigan State University, 2008).

Hadrich, Harrigan and Wolf estimated typical incorporation costs for Michigan livestock operations at $5.94 per acre. Manure stockpile utilization was calculated based on livestock enterprise and manure production levels. Equine manure disposal costs at $200/horse were calculated since land was not available for manure disposal requiring spreading on neighboring land and large stockpiles—often multiple years worth of manure—were typically present (Murphy and Nicholson). Beef and dairy operation disposal costs were calculated as a function of manure produced. Using the tool developed by Hadrich, Harrigan, and Wolf manure stockpile utilization cost was converted to a per acre cost at $37.43/acre for beef and $149.46/acre for dairy. Poultry manure stockpile utilization cost $42.77 per ton (Young et al.).

To prohibit livestock from waterways, a common fence consisting of barbed wire, steel t-posts, wooden posts, and t-post clips with one post every twelve feet and a wood post between every four steel posts was assumed. Using this fence, for example, the average amount of stream bank fencing installed was 1,695 feet at a cost of $945. Controlling run-off involved installing vegetative buffers. Run-off control for dairy and beef farms with greater than 1,000 animal units was valued at $1.42 per AU and $4.69 per AU for all other farms (Vollmer-Sanders, Batie, and Wolf). Following Marlado a vegetative buffer installed for equine operations was estimated to cost $1,300. In some instances a farm was required to install a manure storage facility or milk house-water facility to contain run-off. The cost of controlling waste run-off by building a storage facility was calculated using Harrigan's results where the cost was for example, \$582 per AU for a 100 AU herd and \$259 per AU for a 1,000 AU herd.

Cost to implement corrective practices to mitigate verified complaints varied by livestock enterprise and farm size (Table 2d). Across all farms, dairy operations resulted in the highest average cost of \$16,502. The average dairy CAFO corrective practice cost of \$27,657 was almost twice the amount for dairy AFOs at \$14,117. Beef AFOs average corrective practice cost was higher than beef CAFO cost since the majority of beef AFOs were required to install stream bank fencing. Poultry AFOs were most commonly required to implement MMSPs which resulted in a higher average cost than poultry CAFOs who were required to provide soil analysis and incorporate manure. Swine operations had the lowest average cost for corrective practices demonstrating their awareness of environmental complaints and ability to be pro-active in prevention of complaints.

Table 2d. Average Costs to Implement Corrective Practices

	All Farms		CAFO[1]		AFO[2]	
Enterprise	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
			($)			
Beef	4,809	8,322	1,847	1,691	4,983	8,525
Dairy	16,592	55,680	27,657	95,724	14,117	41,977
Swine	1,421	1,020	1,822	1,559	1,296	783
Equine	3,124	7,089	--	--	3,124	7,089
Poultry	5,477	9,665	2,070	1,297	8,883	13,176
Crop	980	1,076	--	--	980	1,076
Combination Livestock	3,771	7,568	--	--	3,782	7,678
Other Livestock	748	693	--	--	748	693

[1] CAFOs (Concentrated Animal Feeding Operations) are livestock operations with greater than 1,000 AU.

[2] AFOs (Animal Feeding Operations) are livestock operations with less than 1,000 AU.

We examined a log-level regression on those observations with positive corrective practices costs to determine individual farm characteristics influencing these costs expressed as

$$\log(C_i) = X\beta + \varepsilon_i \tag{2}$$

where C_i is cost of implementing corrective practices required to mitigate a verified complaint, **X** denotes an array of variables that are hypothesized to affect cost of implementing corrective practices, β is a vector of parameters, ε_i is the error term, and i farm index.[5] We assumed that ε_i is normally distributed which allows estimation of an OLS regression from equation (2) using maximum likelihood techniques (Wooldridge 2002; 2003).

As in the probit estimation, the base scenario was an odor complaint issued in the Spring for a dairy farm using long-term storage. Results are presented in Table 2e. Receiving a surface water complaint was predicted to cost 45% more than receiving an odor complaint. This resulted in an estimated average cost of $7,326 for implementing the necessary corrective practices to mitigate a surface water complaint compared to an

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[5] We initially examined the probability of a verified complaint followed by a conditional cost of mitigating the complaint using the Heckman two-step procedure where the first step determined the factors affecting the probability of a verified complaint (equation 1). The results from estimating the probability of verified complaints (step 1) excluding county characteristics were used to estimate the inverse mills ratio to test for selection bias in the second step. The inverse mills ratio included in the estimation of equation (2) was not significant indicating no evidence of selection bias and allowing for independent evaluation of equation (2).

odor complaint.[6] Surface water complaints required the most expensive corrective practices implemented on farms.

Increasing the number of animal units on the farm increased corrective practice costs by 0.03%. This translated into a $3.87 cost increase at the mean for each additional animal unit. The probit analysis above revealed that as the number of animal units increased on a farm the probability of a verified complaint decreased. However, when a verified complaint was realized, the costs were higher for larger livestock operations. Large farms must have adequate manure storage and apply this manure within a short period of time, leading to potential verified complaints regarding incorporating manure and waste run-off. Also, larger dairy farms were often required to install run-off control structures, which had declining cost on a per animal unit basis, but resulted in a higher total cost than smaller operations.

Corrective practice costs for swine and equine operations were 77% and 96% less than dairy operations costs, respectively. Equine operations often stockpile manure near property lines or wooded areas without containment walls which could lead to potential waste run-off and potential high corrective practice costs. The average equine herd size with a verified complaint was 32 animal units (16 horses) on 29 acres compared to 360 animal units on 576 acres across all livestock enterprises. While the corrective practice costs for equine operations were lower than dairy operations, they are still significant when holding all other factors constant.

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[6] The estimated average cost of the surface water complaint was adjusted as outlined in Wooldridge (2003) by regressing the coefficient vector of corrective practice costs on the predicted corrective practice costs estimated in equation (2) with no constant at the data means for the explanatory variables.

Corrective practices costs increased by 0.1% for each additional day needed to implement the required corrective practices. The total cost increased by $15.01 at the mean for each additional day it took to mitigate a verified complaint. Incorporating manure or taking soil or manure samples takes little time, which may result in a lower corrective practice costs. However, installing stream bank fencing and controlling run-off require longer implementation time.

Table 2e. Explaining Corrective Practice Costs Required to Mitigate Verified Complaints

Variable	Coefficient		Standard Error	P-value
Complaint Type [1]				
Groundwater	0.4245		0.3524	0.2290
Surface water	0.4549	*	0.2454	0.0650
Combination complaint	-0.1202		0.2992	0.6880
Other complaint	0.3295		0.5662	0.5610
Farm Characteristics				
AU	0.0003	***	0.0001	0.0140
Distance	-0.0165		0.1962	0.9330
Days to implement	0.0012	***	0.0006	0.0400
Manure Storage [2]				
No storage	0.1568		0.3248	0.6300
Short-term	-0.0153		0.2445	0.9500
Livestock Enterprise [3]				
Beef	-0.4203		0.2863	0.1430
Swine	-0.7661	**	0.3531	0.0310
Equine	-0.9636	***	0.2621	0.0000
Poultry	-0.6408		0.6695	0.3390
Crop	-1.0849		0.7759	0.1630
Other livestock	-1.3726		0.9932	0.1680
Combination livestock	-0.3328		0.3904	0.3950
Seasonal factors [4]				
Summer	0.0003		0.2224	0.9990
Fall	0.0962		0.2837	0.7350
Winter	-0.2200		0.2541	0.3870
Year	-0.0111		0.0449	0.8050
Constant	29.4330		89.9102	0.7440

Table 2e cont.

Prob F(20,321)	0.0001
Pseudo R-square	0.1441
Predicted probability at mean	0.0908
Sample size	342

[1] Base complaint type = odor

[2] Base livestock type = dairy

[3] Base manure storage type = long-term

[4] Base season = spring

*** Significant at 1% level

** Significant at 5% level

* Significant at 10% level

.5 Conclusions

We explored the relationship between citizen complaints, livestock production characteristics, county level characteristics, and costs associated with corrective practices implemented on Michigan livestock farms. Farms that received surface water and combination complaints as compared to odor were more likely to have a verified complaint. In contrast an increase in the number of animal units decreased the probability of a verified complaint. Swine and poultry operations were found to have a decreased probability of receiving a verified complaint. The implication is that poultry and hog farms may be justified in higher expenditures to control odor even though it is not currently a legal environmental compliance issue.

Verified complaints and corrective practices were required for the majority of complaints issued. The corrective practices required to mitigate surface water complaints resulted in the highest costs. Surface water control is a necessity in a state surrounded by four of the five Great Lakes. Surface water complaints were received by all livestock groups and indicate the importance of education and assistance to ensure livestock operations are controlling potential run-off.

Dairy operations realized the highest costs to implement corrective practices to mitigate verified complaints. This may be due to the manure and milk-house wastewater handling technology set common to dairy farms built prior to the recent stringent regulations. In addition, swine and poultry farms have a history of being relatively pro-active regarding environmental concerns.

Manure management for equine facilities is becoming increasingly important due to number of horse facilities with a limited land base to properly store and dispose of manure. Horse farms, even though they had less than four horses on average, often were required to dispose of manure stockpiles and control run-off (United States Department of Agriculture, 2008). These practices can become very costly for operations with a small number of animals.

The results identified potential areas of improvement for voluntary programs, such as Michigan's Right to Farm program. Voluntary programs are designed to help producers follow environmental guidelines with the objective of avoiding fines and possible legal actions. The results support continued programs for producer and public education as well as the continued support of cost share programs which provide partial funding for operations to update their manure storage facilities and install stream bank fencing, the two most common and expensive capital investment corrective practices implemented on farms.

REFERENCES

Bundy, L., D. Wolkowski, J. Peters, and C. Laboski. "Avoiding Soil Sampling and Testing Pitfalls in Qualifying For Government Programs Requiring a Nutrient Management Plan." *Wisconsin Crop Manager.* July 2006. Online. Available at http://ipcm.wisc.edu/WCMNews/tabid/53/EntryId/103/Avoiding-Soil-Sampling-and-Testing-Pitfalls.aspx. [Accessed March 2009.]

Cohen, M.A. "Empirical Research on the Deterrent Effect of Environmental Monitoring and Enforcement." *Environmental Law Rep.* 30,4(2000):10245-10252.

Dasgupta, S. and D. Wheeler. "Citizen Complaints as Environmental Indicators: Evidence from China." Working Papers-Environment. Pollution, Biodiversity, Air Quality. 1704. The World Bank, Washington D.C., 1997.

Eckert, H. "Inspection, Warnings, and Compliance: The Case of Petroleum Storage Regulation." *Journal of Environmental Economics and Management* 47,2(2004):232-259.

Environmentally Concerned Citizens of South Central Michigan. Online. Available at http://nocafos.org/. [Accessed March 2009.]

Hadley, G., S. Harsh, and C. Wolf. "Managerial and Financial Implications of Major Dairy Farm Expansions in Michigan and Wisconsin." *Journal of Dairy Science* 85,8(August 2002):2053-2064.

Hadrich, J.C., T.M. Harrigan, and C.A. Wolf. "Economic Analysis of Livestock Manure Handling Systems in the Great Lakes Region." Working Paper. 2009.

Hadrich, J.C., C.A. Wolf, J.R. Black, and S.B. Harsh. "Incorporating Environmentally Complaint Manure Nutrient Disposal Costs into Least-Cost Ration Formulation." *Journal of Agricultural and Applied Economics* 40,1(April 2008):287-300.

Harrigan, T.M. "Simulation of Dairy Manure Management and Tillage Systems." Unpublished Ph.D. Dissertation, Department of Agricultural Engineering, Michigan State University, 1995.

Heyes, A. "Implementing Environmental Regulation: Enforcement and Compliance." *Journal of Regulatory Economics* 17,2(2000):107-129.

Huang, H. and G.Y. Miller. "Citizen Complaints, Regulatory Violations, and Their Implications for Swine Operations in Illinois." *Review of Agricultural Economics* 28,1(2006):89-110.

Maraldo, D. "A Pollution Reduction Optimization Analysis for the Lower Fox River Basin and Green Bay Area of Concern." Online. Available at http://www.uwgb.edu/watershed/REPORTS/Symposium/2008/Poster-I_Cadmus_Final.pdf. [Accessed March 2009.]

Michigan Information Center, State Budget Office. "Estimates Population of Michigan Counties, 1990-1999." April 2000.

Michigan Department of Agriculture. Michigan Commission of Agriculture. "Generally Accepted Agricultural and Management Practices for Site Selection and Odor Control for New and Expanding Livestock Production Facilities." March 2008a.

________. Michigan Commission of Agriculture. "Generally Accepted Agricultural and Management Practices for Manure Management and Utilization." March 2008b.

Murphy, M. and D. Nicholson. "Manure Management Practices of 20 Horse Ranches in Marin County." Marin Resource Conservation District and Marin County Stormwater Pollution Prevention Program. 2002.

Sierra Club. "Living a Nightmare: Animal Factories in Michigan." Online. Available at http://www.sierraclub.org/factoryfarms/nightmare_documentary.asp [Accessed March 2009.]

United States Census Bureau. State Population Datasets-County Population Datasets. 1997, 2002. Online. Available at http://www.census.gov/popest/datasets.html. [Accessed December 2007.]

United States Department of Agriculture. U.S. Census of Agriculture. State and County Reports. 1997, 2002. Online. Available at http://www.agcensus.usda.gov/. [Accessed December 2007.]

United States Department of Agriculture-National Agricultural Statistics Service (USDA-NASS). 2007 Equine Survey Summary. NR-08-04, Lansing, MI, January 2008.

Vollmer-Sanders, C., S. Batie, and C.A. Wolf. "Implementing a voluntary environmental assurance program in Michigan" *Under Review.*

Wooldridge, J. M. *Introductory Econometrics, A Modern Approach.* 2nd ed. Mason, Ohio: South-Western College Publishing, 2003.

Wooldridge, J. M. *Econometric Analysis of Cross Section and Panel Data.* Cambridge, Massachusetts: The MIT Press, 2002.

Young, K., C.I. Carreira, H.L. Goodwin, and E. Wailes. "Economics of Transporting Poultry Litter from Northwest Arkansas to Eastern Arkansas Cropland." Selectedpaper for the Southern Agricultural Economics Association, February 2005.

CHAPTER 3: ECONOMIC COMPARISON OF LIQUID MANURE TRANSPORT AND LAND APPLICATION

3.1 Introduction

On many livestock operations farm managers have transitioned from daily manure hauling to long-term manure storage. Increased herd sizes on a smaller number of farms have resulted in increased manure with greater hauling distance to fields for land application. Applying manure on a limited land base creates management challenges for protecting surface and groundwater quality. Many states have adopted best management practices for manure use as a condition of Right to Farm Act protection (Michigan Department of Agriculture, 2008) which specifically address waste run-off control and management. Such practices include long-term manure storage, manure application rates based on soil test levels and limited winter-spreading. The need for cost effective options has caused farmers to evaluate and change their manure hauling systems.

Suitable working days are the days available in a scheduled period during which field operations can be performed (Harrigan et al, 1996; Rotz and Harrigan, 2005). If manure hauling delays crop tillage and planting, the number of suitable days for planting will decrease and decrease crop yield. Current options in manure transport and land application vary greatly in labor, machinery requirements, ownership and operating costs, and compatibility with the environment. Labor hours are a function of the machinery set, hauling distance, and spreader capacity. If a farm manager has a poorly designed manure hauling system, delays in manure transport and land application may cause delays in crop tillage and planting. Harrigan et al. (1996) evaluated the effect of manure hauling in livestock-based cropping systems for a 150 and 400-cow dairies in Michigan. Labor availability was one 10 hr-person-day/day with the 150-cow herd and three 10 hr-person-days/day with the 400-cow herd. Increased labor on the 400-cow dairy allowed parallel manure application, tillage and planting operations and allowed field work to be completed within the time available.

Decision support systems to evaluate livestock manure as a nutrient source have been developed. Koehler and Lazarus (2009) developed a spreadsheet-based decision tool to calculate the value of manure in Minnesota. Farm inputs included livestock enterprise (beef, dairy, swine and poultry), type of manure (solid or liquid manure), volume of manure, manure analysis, acres available for land application, manure application method (broadcast or injection), planned application rate, crop nutrient needs, and commercial fertilizer cost. Manure application rates were calculated for nitrogen availability and phosphorus limiting application rates. Commercial fertilizer prices were used to calculate the value of manure. Machinery costs were not included.

Leibold and Olsen (2007) developed a spreadsheet-based cost calculator for swine manure to evaluate swine manure application with three different Iowa crop rotations. User inputs included the number and size of hogs, average manure analysis, 5-year average crop yield, planned application rate, and fertilizer prices. A base hauling cost of 0.26 ¢/L (1¢/gal) for liquid manure was assumed with a surcharge of 0.026 ¢/L-mile (0.1¢/gal-mile) for hauling. The cost calculator did not restrict manure application rates based on nitrogen availability or phosphorous limitations.

Whole-farm simulation models have been developed to evaluate farming systems with manure management as a sub-model (Borton et al., 1995; Harrigan et al, 1996; Rotz et al., 2008). The Integrated Farm System Model (IFSM) uses simulation to evaluate production costs, incomes, and economic returns of the farming operation based on local weather data (Rotz et al., 2008). The model simulates forage production on dairy farms with sub-models evaluating cropping systems, manure production, and return of nutrients back to the land. Borton et al. (1995) expanded DAFOSYM, an earlier version of IFSM, to compare the performance and economics of manure hauling systems and interaction with feed production on dairy farms. Net return over feed and manure costs was $25/cow at distances greater than 5 km (3 mile) for truck-drawn nurse tanks for over-the-road transport. Harrigan et al. (1996) used DAFOSYM to evaluate the effect of manure hauling systems on timeliness of tillage and planting.

Koelsch et al. (2007) developed a decision support system that included the feeding, cropping system, and costs associated with the manure hauling system. User inputs included animal numbers, body weight, ration formulation, housing, manure analysis, crop yield and fertilizer needs, manure application method (spreader tank, towed hose, and big gun), and average distance to field. Equipment size and travel speed was defined by the user and used to calculate field application time, road travel time, set-up time, and manure application rate.

Accounting for manure hauling system costs must include the major components of the manure hauling operation while providing a flexible tool for evaluating farm-specific manure hauling system decisions. Timeliness of tillage and planting is dependent on manure hauling time. When planning equipment purchases, farmers must be able to estimate manure hauling time as a function of spreader capacity and hauling distances. Farmers must also select manure hauling systems in a cost effective and environmentally compliant manner. There is a need for a user-friendly decision support system that provides an accurate estimate of time needed for manure pumping, transport, and land application as a function of hauling distance, spreader capacity, manure equipment cost, labor, and the nutrient value of manure. Accurate cost estimates and hauling time will facilitate efficient comparison of cost-effective alternative systems to aid manure movement between livestock and crop producers.

3.2 Objectives

There is a need for a user-friendly decision support system that provides an accurate estimate of cost, time needed for manure pumping, transport, and land application, and the nutrient value of the manure. Specific objectives of this work were to:

1. Develop a spreadsheet-based model (MANURE$HAUL) to estimate manure hauling cost, labor requirements and nutrient value for commonly used top-loading tank spreader systems.
2. Validate the model by comparing estimated hauling costs and time with those reported by two Michigan farms
3. Develop a model in equation for estimating the cost of commonly used tank spreader system as a function of tank volume and transport distance

3.3 Model Development

A spreadsheet-based model, MANURE$HAUL, was developed to evaluate the effect of machinery set and hauling distance on hauling capacity, time, and cost. MANURE$HAUL estimates the manure hauling rate as a function of hauling distance and spreader capacity. Ownership and operating costs were calculated for tractors, trucks, manure spreaders, nurse tanks, agitation and pit pumps, and tillage equipment.

Nutrient use was based on the Tri-state fertilizer recommendations (Vitosh, Johnson, and Mengel, 1995).

3.3.1 Manure Hauling Rate

Liquid manure production for beef, dairy, and swine was based on livestock enterprise, animal size and number of animals on the farm (MWPS, 2004). The manure hauling rate was calculated for top-loading tractor-drawn spreader tanks and spreader tanks with truck-drawn nurse tanks for over-the-road transport to a tractor-drawn spreader in the field. Machinery system-specific coefficients were used to estimate hauling capacity as a function of spreader volume, material flow rates, transport distance, and support time for loading and unloading spreaders (Harrigan, 2009).

Three manure hauling systems were used: (1) tractor-drawn spreader tank, (2) truck-mounted spreader tank, and (3) truck-drawn nurse tanks for over-the-road transport to a tractor-drawn spreader tank for field spreading. The truck-drawn nurse tanks were equal to or twice the volume of the tractor-drawn spreader tank in the field. Hauling rates were estimated for standard and high speed tractors. Hauling capacity decreased as hauling distance increased. The hauling capacity of truck-mounted spreaders was similar to tractor-drawn spreaders when hauling near the storage structure. Truck-mounted spreaders had faster over-the-road transport speeds than tractor-drawn spreaders which provided an advantage with longer hauling distances. Truck-drawn nurse tanks for over-road-transport to a tractor-drawn spreader in the field provided greater hauling capacity for longer distances. When hauling near storage, truck-drawn nurse tanks had idle time in waiting to transfer manure to the tractor-drawn spreader. Two truck-drawn nurse tanks hauling to a tractor-drawn spreader required three operators compared to a one operator for a tractor-drawn spreader tank or truck-mounted spreader.

MANURE$HAUL users can define the type and number of machinery sets to be used with each farm. For example, a farm may choose to use two tractor-drawn spreader tanks in parallel rather than two truck-drawn nurse tanks with a tractor-drawn spreader. Broadcast application, broadcast application with tillage incorporation, and injection were the three manure application methods. Broadcast application with tillage incorporation required an additional tractor and tillage equipment for manure incorporation. Slurry injection decreased the manure hauling capacity compared to broadcast application and resulted in greater downtime for repair and maintenance.

3.3.2 Equipment costs

Equipment ownership costs included depreciation, interest, taxes, housing, and insurance. Operating costs included repairs and maintenance, fuel, lubrication, and labor. Total hauling cost is the sum of ownership and operating costs. Purchase prices were collected for four equipment categories: tractors, tank spreaders, agitators and pumps, and tillage equipment for manure incorporation. Annual and hourly ownership and operating costs were calculated for all items specified in Table 3a.

Table 3a. Manure Hauling System Equipment

Tractor/Truck (for)	Manure Spreader	Agitator and Pump	Incorporation
▪ Manure spreader	▪ Slurry	▪ Small pit pump	▪ Injector System
▪ Agitation	▪ Truck-mounted	▪ Medium pit pump	▪ Tandem Disk
▪ Incorporation	▪ Nurse tank	▪ Large pit pump	▪ Field Cultivator
▪ Truck-mounted Spreader		▪ Small lagoon pump	▪ Combination Tool
▪ Truck for nurse tank		▪ Large Lagoon pump	

Purchase price was collected for a range of tractor power (pto-kilowatt, pto-pto-hp) using the on-line "build your own" tractor utility for Case IH and John Deere equipment. Prices were calculated for 36 diesel-powered, fixed frame (non-articulating) wheeled tractors ranging from 56-205 pto-kW (75-275 pto-pto-hp). All list prices were for new tractors effective October 2008. Estimated price functions for new tractors based on the data collected are presented in table 3b.

The purchase price for used tractors was based on auction data for AGCO-Allis, Case-IH, and John Deere tractors (Iron Solutions, 2006). The average used price for ten to twenty year old tractors was collected for 116 diesel-powered, fixed frame (non-articulating) wheeled tractors ranging from 56-194 pto-kW (75-260 pto-pto-hp). The used tractor price functions based on a linear regression of tractor power on sale price are presented in table 3b.

Tank spreader purchase prices were collected from three manufacturers. Tank capacities ranged from 6,813-35,957 L (1,800-9,500 gal). Company representatives indicated the most common options selected for the spreader tanks. Estimates for truck-mounted and truck-drawn tanks were supplied by custom applicators. In Michigan, refurbished gasoline tankers are typically used as nurse tanks for manure transport from the manure storage facility to a tractor-drawn tank spreader in the field. Custom applicators reported that the purchase price of a used gasoline tank was approximately $10,000 plus an additional $15,000 investment for hydraulics, pumps and other modifications. The purchase price for truck-mounted spreader tanks were provided by one manufacturer for tanks ranging from 11,923-18,168 L (3,150-4,800 gal). Truck-mounted purchase price functions are presented in table 3b.

Semi-tractors were used with truck-drawn nurse tank systems. Based on discussions with three custom manure applicators, an average age of semi-tractors ranged from 5-15 years with an average age of 10 years. A representative purchase price was $10,000 with an additional $10,000 investment for a hydraulic (wet) kit for the truck. A truck-drawn nurse tank list price was $45,000--$25,000 for a nurse tank and $20,000 for the truck.

Farmers generally have three options for liquid manure application: 1) inject manure directly into the soil during application, 2) surface broadcast, and 3) surface broadcast with incorporation. Injection reduces the number of passes over the field and improves nitrogen recovery, but reduces the manure hauling rate (Harrigan, 2009). Cost information was collected for injection equipment from three custom manure applicators and two spreader tank manufacturers. Mounting a toolbar for injectors and other alterations to a manure spreader were valued at $9,000 with an additional $1,600 per injector installed on the toolbar. In MANURE$HAUL, a toolbar with 6 injectors was used for equipment comparisons.

Manure incorporation requires the farmer to use a tractor and tillage tool to incorporate manure into the soil. Purchase price data was collected for tandem disks, field cultivators, and combination tillage tools using on-line "build your own" equipment options for Case-IH and John Deere tillage equipment (Case-IH, 2009; Deere and Co, 2009). All purchase prices were effective February 2009 for 44 tandem disks ranging in field width from 3.5-10.36 m (11.5-34 ft.), and 39 field cultivators ranging 5.5-18.3 m (18-60 ft.). Estimated tillage equipment purchase price functions are presented in table 3b.

Table 3b. Estimated equipment list price functions

Equipment	Price (Y)	Intercept	Slope	X1	R2	X variable
Tractors						
New tractor	Price_{NT}	-32,582	884	pto-hp_{NT} pto-kW_{NT}	0.90	pto-hp_{NT} pto-kW_{NT}
Used tractor	Price_{UT}	7,470	183	pto-hp_{UT} pto-kW_{NT}	0.43	pto-hp_{UT} pto-kW_{UT}
Semi-tractor	20,000					
Truck-mounted truck	50000					
Spreaders						
Slurry tank	Price_{S}	-3,786 (-3,786)	2.91 (11)	L_S (gal_S)	0.87	L_S = liters (gal_S = gallons)
Truck-mounted tank	Price_{TM}	18,219 (18,219)	0.63 (2.4)	L_{TM} (gal_{TM})	0.97	L_{TM} = liters (gal_{TM} = gallons)
Nurse tank	25,000					
Injectors & toolbar	Price_{I}	9,000	1,600	Injectors	--	Injectors=number of injectors
Tillage Equipment						
Tandem disk	Price_{TD}	-884 (-884)	5,117 (1,560)	fieldm_{TD} (fieldft_{TD}	0.89	fieldm_{TD} =field width (m) (fieldft_{TD} =field width (ft))
Field cultivator	Price_{FC}	-2.534 (-3,068)	3,391 (1,125)	Fieldm_{FC} (fieldft_{FC})	0.76	Fieldm_{FC} =field width (m) (fieldft_{FC} =field width (ft))
Combination tool	Price_{CT}	2,577 (2,404)	5,691 (1,735)	fieldmt_{CT} (fieldft_{CT}	0.84	fieldm_{CT} =field width (m) (fieldft_{CT} =field width (ft))

3.3.3 Ownership costs

Straight line depreciation was calculated as the difference between the beginning and ending value for a 10 year economic life. Remaining values were based on list price, tractor age, and annual hourly use (ASABE, 2007). Remaining value coefficients for agitators and pumps are not provided in the ASABE Standard (EP496), therefore coefficients for the nearest equipment in size and use was used, which was "miscellaneous farm equipment".

New tractors were assumed to have a base annual hourly use of 500 hours and 350 hours for used tractors. Calculated manure hauling hours were added to the base use hours for new and used tractors. Manure spreader base hours were calculated in MANURE$HAUL as time needed for manure transport and land application. Time for pumping and agitation was estimated as the manure pumping time plus eight hours for the initial set-up and agitation for each of two pumping events each year. The salvage value of equipment was estimated as:

$$(1) \qquad SV_n = (1 - RV_n)*LP$$

where SV_n was salvage value of equipment in year *n*, RV_n was remaining value of equipment in year *n*, and *LP* was equipment list price.

MANURE$HAUL valued taxes, housing, and insurance at 1%, 0.75%, and 0.25% of the list price of equipment, respectively (ASABE, 2007). The real interest rate was set at 5% (Edwards, 2005).

3.3.4 Operating costs

Annual operating costs included repairs and maintenance, fuel, lubrication, and labor. Repair and maintenance costs were based on accumulated use (ASABE, 2007). When repair factors were not listed in the ASABE standard, a composite of repair factors was used to best reflect repair and maintenance costs provided by custom manure applicators. Repair factors were not provided for trucks, manure spreaders and agitator pumps. Repair factors for manure spreaders, agitators, pumps and other equipment are listed in table 3c. Repair and maintenance cost factors for injectors were estimated based on information from three custom manure applicators. Repair and maintenance costs were assumed to be $240/injector point for every 405 ha (1000 ac) of use in loam or sandy-loam soil.

Table 3c. Repair factors for trucks, manure spreaders, and agitators and pumps

Equipment	RF1	RF2	Similar machinery
Small Tractors , <60 kW (<80 hp)	0.007	2.0	--
Medium Tractors, 60-112 kW (80-150 hp)	0.007	2.0	--
Large Tractors, >112 kW (>150 hp)	0.007	2.0	--
Truck*	0.007	2	2 wheel drive and stationary tractors
Manure Spreader*	0.16	1.6	Forage wagons and fertilizer spreaders
Agitators and pumps*	0.22	1.8	Forage blowers
Disk	0.180	1.7	--
Field Cultivator	0.270	1.4	--
Chisel Plow	0.280	1.4	--

*Composite repair factors

Fuel use was estimated as 0.22 L/pto-kW-h (0.044 gal/pto-hp-h) for tractors (ASABE, 2007) and 0.086 L/pto-kW-h (0.0170 gal/pto-hp-hr) for trucks (Harrigan, 2001). Lubrication was estimated as 15% of the fuel cost (ASABE, 2007). Labor was valued at $12/hr (Black et al, 2008; Koelsch et al., 2007). Labor hours for each operation were those calculated by MANURE$HAUL plus 10% for set-up and scheduled maintenance. Agitation and pumping hours were estimated based on a pumping rate of 7,192 L/min (1,900 gal/minute) plus an additional 16 hours (eight hours, two times per year) for set-up and agitation. Tillage hours were based on machine width, a travel speed of 8 km/hr (5 mph), and tillage implement field efficiency of 85%.

3.4 Nutrient value of manure

The value of manure nutrients applied to the land is a function of the nutrient content of manure; quantity of manure applied, and method of application. Tillage incorporation or injection conserve volatile nitrogen and prevents run-off. Injection reduces the odor associated with land application but results in greater downtime for repairs and maintenance for injection equipment. A broadcast application with immediate incorporation is generally faster than injection, but nitrogen losses can be significant if there is a time lag between manure application and incorporation.

3.4.1 N volatilization losses

The best way to recover costs associated with manure storage and handling is to apply the manure at an agronomic rate, account for manure nutrients, and reduce commercial fertilizer purchases. Non-mobile nutrients such as potassium (K) and phosphorus (P) are easy to account for, but calculating nitrogen (N) credits is a challenge. Manure contains nitrogen in inorganic and organic forms. Organic N is not available for crop growth until it is mineralized to ammonium (NH_4^+). Ammonium N is fairly stable and available for plant uptake, but a portion is immobilized by microbial biomass, and nitrifying bacteria convert NH_4^+ to nitrate (NO_3^-) which is subject to loss by leaching or denitrification and subsequent loss to the atmosphere. Volatile ammonia (NH_3) is transformed from NH_4^+ and can be lost to the atmosphere after land application.

Nitrogen lost to the atmosphere is not available for crop production. Injecting the slurry into the soil or incorporating it with tillage is the most effective ways to reduce

NH_3 losses. Ammonia emissions increase with an increase in temperature and wind speed, and decrease with an increase in relative humidity. Organic N becomes available for crop growth over time as it is mineralized to the ammonium form. Available organic N is defined as:

$$(2) \qquad \text{Available Organic } N = (\text{Total } N - NH_4\text{-}N) * m$$

where *Total N* is total nitrogen, NH_4-N is ammonium, and *m* is the mineralization factor. The mineralization factor, ***m***, describes the fraction of *organic N* available for plant use in the first season following manure application (MWPS, 1993).

Plant available N (PAN) is a function of total soil N, the N available in soil for crop use, amount of organic N mineralized, and the amount of NH_4-N in the soil. Jacobs (1995b) estimated NH_4-N volatilization losses for surface broadcast and manure injection in Michigan as a function of the time delay between manure application and incorporation (Table 3d).

Table 3d. Estimated N volatilization losses by manure application method

Days to Incorporation	NH_4-N Retained (%)	NH_4-N Lost (%)
Injection	100	0
0-1 day	70	30
2-3 days	40	60
4-7 days	20	80
>7 days	10	90

*Source: Jacobs (1995b), Table 3.

3.4.2 Fertilizer recommendations

Fertilizer recommendations for field crops are a function of the crop grown, expected crop yield, soil type, and soil test levels. Field crop fertilizer recommendations for Michigan, Ohio and Indiana are published in the Tri-State Fertilizer Recommendations (1995) and follow a "build-up", "maintenance" and "draw-down" approach to managing soil phosphorus. Soil test results below a critical level indicate a nutrient deficit and a need to "build-up" or raise soil test levels for optimal crop yield. Critical and maintenance limits vary by crop, soil type, and state (Vitsosh, Johnson, and Mengel, 1995). Soil test results at the maintenance level result in a level of nutrients to provide optimal crop yield. Soil test values greater than the "maintenance" level indicate a surplus and the need to "draw-down" or reduce nutrients to "maintenance" levels. For example, for loam soil in Michigan, Bray P1 soil tests results with less than 167 kg/ha (74 lb/ac) allow a "build-up" of soil phosphorus whereby manure can be applied at N-removal application rates. Because manure application rates based on N typically exceed crop P_2O_5 removal, the soil P level increases. Fields testing 167-336 kg/ha (75-299 lbs/acre) $P_2O_5$are in the "maintenance" zone and manure or commercial nutrients can be applied at crop removal rates. Phosphorus generally limits manure application at the crop "maintenance" level. Fields testing 337 kg/ha (300 lb/ac) of P_2O_5require a "draw-down" of soil phosphorus and manure application is not allowed until soil P_2O_5levels drop below 337 kg/ha (300 lb/ac).

Fertilizer recommendations in MANURE$HAUL are based on input by the user for crop grown and expected yield using crop nutrient removal guidelines for Michigan field crops (Warncke et al., 2004). The nutrient content of the manure can be estimated based on typical values for livestock enterprises (MWPS, 2001) or can be provided by the user based on manure analysis results. The quantity of manure nutrients applied was based on the manure application rate manure analysis. Table 3e presents a summary of Bray P1 soil test results, fertilizer recommendations, application rates, and nutrient credit guidelines used in MANURE$HAUL.

Table 3e. Bray P1 soil test results, fertilizer recommendations, manure application rates, and nutrient credit guidelines used in MANURE$HAUL

Bray P1 Soil Test	Units	Soil test classification	Application rate	Nutrient credits
0-167 (0-149)	kg/ha (lbs/acre) P_2O_5	"build-up"	Nitrogen removal	N, P_2O_5 and K
168-336 (150-299)	kg/ha (lbs/acre) P_2O_5	"maintenance"	Phosphorus removal	N, P_2O_5 and K up to crop P_2O_5 removal
337+ (300+)	kg/ha (lbs/acre) P_2O_5	"draw-down"	No application	None

3.5 Procedure

The objective of this work was to develop a flexible, easy-to-use model to describe, evaluate, and compare a range of liquid manure transport and land application systems. The model includes beef, dairy, and swine operations using tractor-drawn tank spreaders, truck-mounted and truck-drawn tank spreaders, and tractor-drawn tank spreader with truck-drawn nurse tanks for over-the-road transport. Manure hauling rates were a function of spreader capacity, distance, and the manure hauling system chosen

(Harrigan, 2009). Manure was applied to fields with injection, surface broadcast, or surface broadcast with incorporation.

Table 3f lists MANURE$HAUL user inputs and default values. Required inputs are: livestock type, number of animals (or volume of manure for land application, L, gal), tractor size (pto-pto-kW, pto-pto-hp), spreader volume (L, gal), crop area (ha, acres), crop yield (kg/ha, ton/acre), soil test results (N, $P_2O_5$and K_2O) and hauling distance to field zones (km, mi).

Manure production and nutrient content are based on the user input for the livestock type, size, and number of animals on the farm. Users can accept the default values or override the calculated manure production and nutrient levels with results of a manure analysis. Tractor, spreader tank, and tillage equipment ownership and operating costs are based on user inputs for tractor size (pto-pto-kW, pto-pto-hp), spreader capacity (L, gal), and equipment width (m, ft), respectively. Manure injector ownership and operating costs are based on user input for the number of injectors used.

The default values for the economic parameters in MANURE$HAUL are listed in Table 3f. Users can change fuel price ($/L, $/gal), labor wage rate ($/h), fertilizer prices ($/kg, $/lb N, $P_2O_5$and K_2O), and the economic life of equipment (5-10 years). Economic parameters that are fixed are fuel use (L/pto-kW-h, gal/pto-hp-h), annual tractor use (hours), real interest rate, taxes, housing, and insurance.

Table 3f. MANURE$HAUL user inputs, defaults, and override values

Parameter	User Input	Default Value	Override	
Animals and Equipment			Yes	No
Beef, dairy, swine*	Number of animals	--	X	
Manure Analysis	N-P2O5-K2O	--	X	
	Manure production	--	X	
Tractor for spreader*	pto-kW (pto-hp)	--	X	
Tractor for agitator*	pto-kW (pto-hp)	--	X	
Tractor for tillage*	pto-kW (pto-hp)	--	X	
Truck for nurse tanks*	pto-kW (pto-hp)	--	X	
Truck for truck-mounted spreader*	pto-kW (pto-hp)	--	X	
Manure spreader*	capacity, L (gal)	--	X	
Nurse tanks*	capacity, L (gal)	--	X	
Injectors*	Number	6	X	
Tillage equipment*	Width, m (ft)	--	X	
Field Zones (1-4)				
Crop acres*	Yield, unit/ha (unit/acre)	--		
	hauling distance, km (mi)	--		
	soil test results	--		
		--		
Economic Parameters				
Diesel fuel price	$/L ($/gal)	$0.46/L ($1.75/gal)	X	
Tractor fuel usage	L (gal)	0.22 per pto-kW-h (0.044 per pto-hp-h)		X
Truck fuel usage	L (gal)	0.086 per pto-kW-h (0.0170 per pto-hp)		X
Labor wage rate	$/hr	$12/hr	X	
Fertilizer prices				
N	$/kg ($/lb)	$1.43/kg ($0.65/lb)	X	
P2O5	$/kg ($/lb)	$2.03/kg ($0.92/lb)	X	
K2O	$/kg ($/lb)	$1.65/kg ($0.75/lb)	X	
Economic life	Years	5-10	X	

Table 3f cont.

Tractor annual use	Hours	500	X
Used tractor annual use	Hours	350	X
Real Interest rate	%	5%	X
Taxes	% of machinery list price	1%	X
Housing	% of machinery list price	0.75%	X
Insurance	% of machinery list price	0.25%	X

*Input values required for MANURE$HAUL to calculate manure hauling costs

As farms consolidate and increase in size they acquire a land base with varying distance for manure application. Delays in manure application in the spring can delay crop planting and reduce crop yield. A well-designed manure hauling system will prevent delays in crop planting in most years (Rotz and Harrigan, 2005). The manure hauling cycle includes time required for loading the spreader, transporting the spreader to the field, unloading the spreader, and transporting the spreader back to the storage structure. Manure hauling rates vary with machinery sets, hauling distance, spreader capacity and other factors (Harrigan, 1997; 2009). A tractor-drawn spreader tank uses one tractor, one spreader tank and one operator, and is an efficient system when hauling within a few mi of storage. An alternative is to use truck-drawn nurse tanks for over-the-road transport to a tractor-drawn spreader in the field. Compared to a tractor-drawn spreader alone, this machinery set requires additional equipment and three operators, but is more cost and labor efficient for greater hauling distances. There is a need for a decision tool to help manure managers evaluate, compare and select machinery systems suitable for a range of hauling distances.

Tractor-drawn spreaders have an advantage when the fields are close to storage because there is no need for in-field nurse tank-to-spreader transfer but the hauling capacity diminishes rapidly as hauling distance increases (Fig 3a). The hauling capacity with a 4.8 km (3 mi) haul is less than one-half the capacity when hauling near storage. Truck-mounted spreaders and tank spreaders working in parallel with nurse trucks for over-the-road transport have an advantage with longer hauls because of their greater road travel speed.

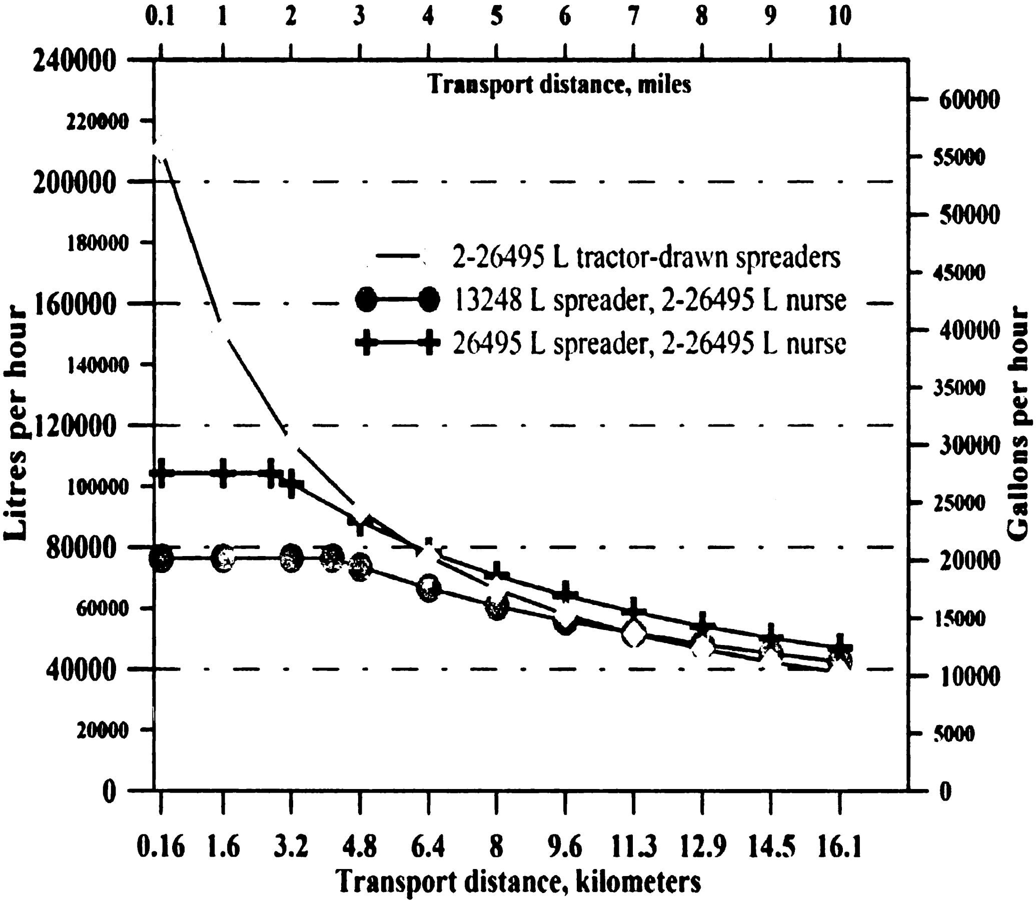

Figure 3a. Hauling capacity of two 26,495 L (7,000 gal) tractor-drawn tank spreaders working in parallel, one 13,248 L (3,500 gal) tractor-drawn spreader in parallel with two 26,495 L (7,000 gal) nurse trucks, and two 26,495 L (7,000 gal) tractor-drawn spreaders in parallel with two 26,495 L (7,000 gal) nurse trucks over 16.1 km (10.1 mile) hauling distance

MANURE$HAUL was used to estimate the costs and labor requirements for two manure transport and land application systems for a representative, 700-cow dairy using (1) two 26,495 L (7,000 gal) tractor-drawn spreaders, and (2) one 26,495 L (7,000 gal) tractor-drawn spreader in the field with two 26,496 L (7,000 gal) truck-drawn nurse tanks for over-the-road transport. The hauling distance was varied from 0.5-8 miles when hauling 6.1 million gallons for broadcast application. Two tractor-drawn spreaders had a lower cost 0.35-0.53¢/L (1.3 to 2 ¢/gal) than one tractor-drawn spreader in the field with two over-the-road transport nurse tanks, 0.53-0.58¢/L (2.0 to 2.2 ¢/gal), when land application was within 3 miles of storage (Fig. 3b). Hauling time ranged from 126 h to 210 h when hauling up to two and one-half miles with the tractor-drawn spreaders and 210 h to 211 h with the tractor-drawn/nurse truck system. Beyond 3 miles the cost for the two tractor-drawn spreaders increased from 0.53 to 1 ¢/L (2.2 to 3.8 ¢/gal) with an eight mile haul while the cost for the tractor-drawn/nurse truck system increased to 3.2 ¢/gal with an eight mile haul. Hauling time was 458 h (22.9 days) with two tractor-drawn spreaders and 365 h (36.5 days) with the nurse trucks with eight-mile hauls. Based on cost and labor requirements for manure transport and land application, nurse truck-based systems had an advantage when the hauling distance was three miles or more. This result was consistent with the experience of custom applicators in the Great Lakes Region of when to switch from tractor-drawn spreaders to nurse truck/spreader-tank systems.

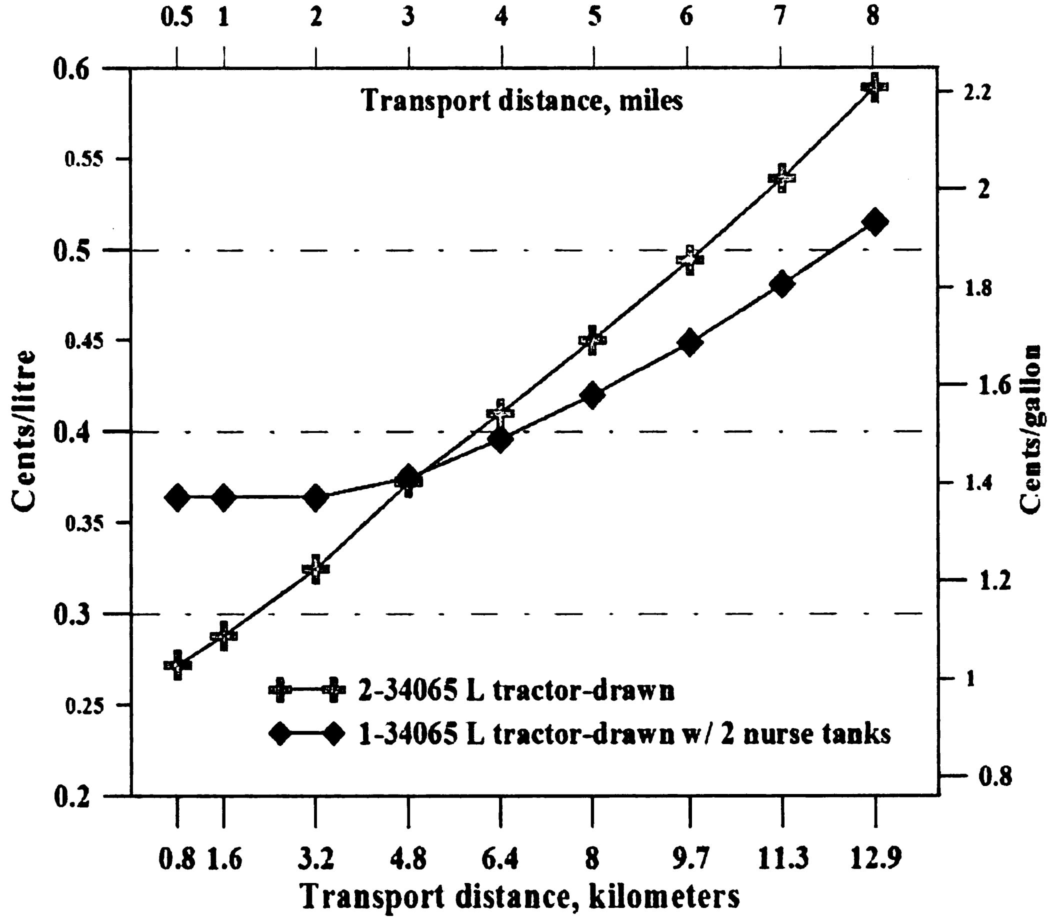

Figure 3b. Manure hauling cost for a 700-cow dairy using two 34,065 L (9,000 gal) tractor-drawn spreaders working in parallel and one 34,065 L (9,000 gal) tractor-drawn spreader in parallel with two 34,065 L (9,000 gal) nurse tanks over 12.9 km (8 miles).

3.6 Representative dairy farm

Many of the questions that manure managers have at the systems engineering level relate to capacity, cost and labor requirements of the manure hauling system. An objective in developing MANURE$HAUL was to create a flexible model that could be use to describe, evaluate and compare a range of manure transport and land application methods. Land application methods include surface broadcast or subsurface injection with tractor-drawn tank spreaders, truck-mounted or truck-drawn tank spreaders, or a tractor-drawn spreader in parallel with nurse trucks for over-the-road transport. To illustrate the ability of the model to describe, evaluate and compare a range of manure transport and land application options, four systems were compared on four representative dairy farms with 175-, 350-, 700- and 1400-cow herds.

The land available for each herd was based on 1.2 ha (3 acres) per cow and a cropping program of corn grain, corn silage and alfalfa on loam soil (Wittenberg and Wolf, 2005). The area allocation for corn grain, alfalfa, and corn silage was typical for Michigan farms with 50% of the area in alfalfa and the remaining land divided between corn grain and corn silage. Sixty percent of the corn ground was planted to corn grain with the remaining land in corn silage. Corn silage was assumed to be grown in fields closest to the farm to facilitate corn silage harvest. Soil test results report the current nutrients available in the soil before the crop is planted. Soil test results allow the farmer to determine if the soil is in a "build-up", "maintenance", or "draw-down" zone following the Tri-state fertilizer guidelines. Fertilizer recommendations as determined by crop nutrient removal for optimal crop yield were determined by estimated yield goals for corn grain and corn silage as listed in Table 3g (Warncke et al., 2004). An average hauling distance was 1.6 km (1 mi) for the 175-cow herd and 2.4, 3.2, 4.8 km (1.5, 2 and 3 mi) for the 350-, 700- and 1400-cow herds, respectively.

Table 3g. Fertilizer recommendations and soil test results for corn grain and corn silage

	Yield	N	P2O5	K2O
Fertilizer recommendation			kg/ha (lbs/acre)	
Corn Grain	8.1 mg/ha	131	54	39
	(130 bu/acre)	(117)	(48)	(35)
Corn Silage	33.6 mg/ha	158	56	134
	(15 ton/acre)	(141)	(50)	(120)
Alfalfa Hay	13.4 mg/ha	302	87	336
	(6 ton/acre)	(270)	(78)	(300)
Soil tests results				
Corn grain		45	90	112
		(40)	(80)	(100)
Corn silage		78	90	157
		(70)	(80)	(140)

Machinery sets were selected to complete manure hauling in approximately twenty 10-hour calendar days or less. Tank size and equipment complements were changed to accommodate greater volumes of manure as herd size and hauling distance increased. Farms have numerous fields at varying hauling distances on their farm. To decrease the number of inputs for fields in MANURE$HAUL, field zones were created. For example, a farm with four fields of varying area planted in corn grain within one mi of the manure storage facility are categorized as one field zone with an average hauling distance of 1.6 km (1 mi). (Table 3h) Tractor power was increased by 15 pto-pto-kW (20 pto-pto-hp) compared to a broadcast application when manure was injected. The machinery sets selected were not necessarily optimal or least-cost systems, rather machinery sets that would likely be used with herds of that size in the Great Lakes Region. Purchase prices for the machinery sets chosen are listed in Table 3i.

Table 3h. Farm characteristics for 175-cow, 350-cow, 700-cow, and 1,400 cow dairy

Animals	175-cow dairy	350-cow dairy	700-cow dairy	1,400-cow dairy
Dairy Cows	175	350	700	1,400
Dry Cows	35	70	140	280
Heifers	88	175	350	700
Manure prod, L	5,781,822	11,554,038	23,108,079	46,216,155
(gal)	(1,527,562)	(3,052,586)	(6,105,173)	(12,210,345)
N, kg	36,100		144,300	288,601
(lbs)	(79,515)	72,150 (158,921)	(317,842)	(635,684)
P2O5, kg	17,408	34,799	69,598	139,196
(lbs)	(38,343)	(76,650)	(153,300)	(306,600)
K2O,kg	22,964		91,754	183,507
(lbs)	(50,582)	45,877 (101,050)	(202,101)	(404,201)
Cropping System		ha, km (acres, miles)		
Field Zone 1:	30.8 ha, 2.4 km	61.5 ha 2.4 km	123 ha, 3.4 km	246.1 ha, 6.8 km
Corn grain	(76 ac, 1.5 mi)	(152 ac, 1.5 mi)	(304 ac, 2.1 mi)	(608 ac, 4.2 mi)
Field Zone 2:	30.8ha, 3.2 km	61.5 ha, 5km	123 ha, 5 km	246.1 ha, 5 km,
Corn grain	(76 ac, 2 mi)	(152 ac, 3.1 mi)	(304 ac, 3.1 mi)	(608 ac, 3.1 mi)
Field Zone 3:	20.6 ha, 0.8 km	40.9 ha, 1.6 km	81.8 ha, 1.2 km	163.5ha 2.4 km
Corn silage	(51 acr, 0.5 mi)	(101 ac, 1 mi)	(202 ac, .75 mi)	(404 ac, 1.5 mi)
Field Zone 4:	20.6 ha, .40 km	40.9 ha, 0.8 km	81.8 ha, 1.9 km	163.5 ha, 1.6 km
Corn silage	(51 ac 0.25 mi)	(101 ac,0.5 mi)	(202 ac, 1.2 mi)	(404 ac, 1 mi)
Average hauling distance	1.6 km (1 mi)	2.41 km (1.5 mi)	3.2 km (2 mi)	4.8 km (3 mi)

Table 3i. Equipment used and size, and estimated purchase price for 175-, 350-, 700-, and 1,400 cow dairy herds

	175-cow dairy		350-cow dairy		700-cow dairy		1,400 cow dairy	
Broadcast application	Size	Purch. Price ($)	Size	Purchase Price ($)	Size	Purchase Price ($)	Size	Purch. Price ($)
Agitator tractor, pto-kW (pto-hp)	75 (100)	25,668	127 (170)	38,173	127 (170)	38,173	127 (170)	38,173
Spreader tractor, pto-kW (pto-hp)	89 (120)	73,540	164 (220)	161,976	179 (240)	179,663	179 (240)	179,663
Tillage tractor , pto-kW (pto-hp)	104 (140)	91,227	134 (180)	126,601	134 (180)	126,601	134 (180)	126,601
Nurse tank truck, pto-kW (pto-hp)	--	--	--	--	--	--	298 (400)	50,000
Spreader tank, L (gal)	11,355 (3,000)	25,978	28,388 (7500)	71,195	34,065 (9000)	86,268	34,065 (9000)	86,268
Nurse tank, pto-kW (pto-hp)	--	--	--	--	--	--	2-34,065 (2-9000)	25,000

Table 3i cont.

Lagoon Pump	Med.	16,500	Large	30,000	Large	30,000	Large	30,000
Tandem disk, m (ft)	5.5 (18)	27,817	7.6 (25)	38,104	9.8 (32)	49,021	9.8 (32)	49,021
Injection Application								
Spreader tractor, pto-kW (pto-hp)	112 (150)	100,071	179 (240)	179,663	194 (260)	197,350	194 (260)	197,350
Toolbar w/injectors	6	18,600	6	18,600	6	18,600	6	18,600

3.7 Results Discussion

MANURE$HAUL was used to estimate manure hauling costs, time, and the value of land applied manure nutrients for representative 175-, 350-, 700-, and 1,400-cow dairy herds. Broadcast, broadcast with immediate incorporation, and injection application were used to compare nutrient recovery and costs.

3.7.1 Labor Requirements

The labor requirement for manure agitation, pumping, transport and application was 16.6, 20.0, 18.7, and 34.6 days for the 175-, 350-, 700-, and 1,400-cow herds, respectively (table 3j). Additional time for manure incorporation with a tandem disk ranged from 3.1 days with the 175-cow herd to 13.6 days with the 1400-cow herd. One 11,365 L (3,000 gal) tractor-drawn spreader tank was able to complete the land application within the time available for the 175-herd, and one 28388 L (7,500 gal) spreader tank was adequate with the 350-cow herd when the average hauling distance was 2.4 km (1.5 mi). Although two nurse trucks were used to increase hauling capacity to fields greater than 4.8 km (3 mi) from storage, one 34,065 L (9,000 gal) spreader working with two 34065 L (9000 gal) nurse trucks was unable to complete manure hauling within the time available for the 1400-cow herd. In such a case the manure manager may choose to purchase additional equipment, work longer days, or custom hire manure hauling and land application services to increase hauling capacity. An alternative management approach would be to include wheat or a small grain in the crop rotation to expand the window of opportunity for land application.

When subsurface injection was used for manure application, time needed for agitation, pumping, transport and land application increased 14%, 18.5%, 19.3%, and 6.8% for the 175-, 350-, 700-, and 1,400-cow herds, respectively, compared to a broadcast application. Injection had less impact on timeliness with the 1400-cow herd because 60% of the manure slurry was hauled more than 4.8 km (3 mi) with truck-drawn nurse tanks. At this hauling distance the tractor-drawn spreader experienced idle time in the field waiting for a nurse truck to arrive. Because of this idle time there was little advantage for broadcast application compared to subsurface injection.

Table 3j. Hauling time and costs for 175-cow, 350-cow, 700-cow dairy, and 1,400-cow dairy using broadcast and injection application

	175-cow dairy	350-cow dairy	700-cow dairy	1,400-cow dairy
Manure volume, L (gal)	5,781,822 (1,527,562)	11,554,038 (3,052,586)	23,108,079 (6,105,173)	46,216,155 (12,210,345)
Hauling distance, km (mi)				
Field Zone 1: Corn silage	0.40 (0.25)	0.8 (0.5)	1.9 (1.2)	1.6 (1.0)
Field Zone 2: Corn silage	0.8 (0.5)	1.6 (1.0)	1.2 (0.75)	2.4 (1.5)
Field Zone 3: Corn grain	2.4 (1.5)	2.4 (1.5)	3.4 (2.1)	5.0 (3.1)
Field Zone 4: Corn grain	3.2 (2.0)	5.0 (3.1)	5 (3.1)	6.8 (4.2)
Average hauling distance	1.6 (1.)	2.4 (1.5)	3.2 (2.0)	4.0 (2.5)
Manure machinery set	1 tractor-drawn spreader	1 tractor-drawn spreader	2-tractor drawn spreaders	2 tractor-drawn spreaders <3 mi, 1 spreader and 2 nurse tanks >3 mi

Table 3j cont.	175-cow dairy	350-cow dairy	700-cow dairy	1,400-cow dairy
Broadcast Application				
Equipment				
Pumping and agitation				
Tractor, pto-kW (pto-hp)	75 (100)	127 (170)	127 (170)	127 (170)
Pump (size)	medium lagoon pump	large lagoon pump	2 large lagoon pumps	2 Large lagoon pump
Manure Hauling				
Spreader tractor,pto-kW (pto-hp)	89 (120)	164 (220)	179 (240)	179 (240)
Spreader tank, L (gal)	11,355 (3,000)	28,388 (7,500)	34,065 (9,000)	34,065 (9,000)
Truck , pto-kW (pto-hp)	--	--	--	298 (400)
Nurse tank, L (gal)	--	--	--	34,065 (9,000)
Incorporation				
Tractor for tillage, pto-kW (pto-hp)	104 (140)	134 (180)	134 (180)	134 (180)
Tillage equipment m (ft)	5.5 (18) tandem disk	7.6 (25) tandem disk	9.8 (32) tandem disk	9.8 (32) tandem disk
Results	175-cow dairy	350-cow dairy	700-cow dairy	1,400-cow dairy
Hauling rate, L/hr (gal/hr)				
Field zone 1: corn grain	32,744 (8,651)	62,528 (16,520)	121,910 (32,209)	92,231 (24,368)
Field zone 2: corn grain	28,795 (7,608)	41,447 (10,950)	94,281 (24,909)	102,831(27,168)
Field zone 3: corn silage	42,339 (11,186)	71,102 (18,785)	172,471 (45,567)	142,235 (37,579)
Field zone 4: corn silage	45,149 (11,928)	80,851 (21,361)	153,635 (40,591)	161,738 (42,731)
Average hauling rate	37,257 (9,843)	63,982 (16,904)	135,574 (35,819)	124,759 (32,961)
Labor				
Pumping, agitation, transport and application, hours (days)	166 (16.6)	200 (20)	187 (18.7)	407 (34.6)
Tillage incorporation, hours (days)	31 (3.1)	44 (4.4)	68 (6.8)	136 (13.6)
Cost				
Agitation, pumping, transport, application; $/h	155.22	259.94	526.51	586.36
¢/L (¢/gal)	0.24 (0.93)	0.29 (1.09)	0.33 (1.24)	0.53 (2.02)
$/ha ($/acre)	22.69 (56.07)	26.62 (65.75)	27.47 (67.88)	36.24 (85.55)
Tillage incorporation, $/h	119.82	134.03	124.97	99.71
¢/L (¢/gal)	0.06 (0.25)	0.05 (0.19)	0.04 (0.14)	0.03 (0.11)
$/ha ($/acre)	5.98 (14.77)	4.72 (11.66)	3.40 (8.40)	2.72 (6.71)
Total cost ¢/L (¢/gal)	0.31 (1.18)	0.34 (1.28)	0.36 (1.38)	0.56 (2.13)

Table 3j cont.

Injection Application				
Equipment				
Manure Hauling				
Spreader Tractor, pto-kW (pto-hp)	112 (150)	179 (240)	194 (260)	194 (260)
Spreader tank, L (gal)	11,355 (3,000)	28,388 (7,500)	34,065 (9,000)	34,065 (9,000)
Truck , pto-kW(pto-hp)	--	--	--	298 (400)
Nurse tank , L(gal)	--	--	--	34,065 (9,000)
Injector	6-point	6-point	6-point	6-point
Results				
Hauling rate, L/hr (gal/hr)				
Field Zone 1: Corn grain	29,092 (7,686)	52,343 (13,829)	102,313 (27,031)	90,737 (23,973)
Field Zone 2: Corn grain	25,893 (6,841)	36,054 (9,525)	81,047 (21,413)	100,843 (26,643)
Field Zone 3: Corn silage	36,726 (9,703)	58,810 (15,538)	140,132 (37,023)	121,516 (32,105)
Field Zone 4: Corn silage	38,928 (10,285)	66,077 (17,458)	126,183 (33,338)	134,296 (35,481)
Average hauling rate	32,660 (8,629)	14,087	112,419 (29,701)	111,848 (29,550)
Labor	175-cow dairy	350-cow dairy	700-cow dairy	1,400-cow dairy
Pumping, agitation, transport and application, hours (days)	188 (18.8)	237 (23.7)	223 (11.35)	435 (36.3)
Cost				
Agitation, pumping, transport, application; $/h	167.81	265.03	533.07	605.43
¢/L (¢/gal)	0.29 (1.09)	0.33 (1.25)	0.38 (1.45)	0.60 (2.23)
$/ha ($/acre)	29.35 (72.52)	31.66 (78.23)	19.50 (48.16)	38.69 (95.59)

3.7.2 Hauling costs

The ownership and operating costs for manure agitation, pumping, transport and land application ranged from about $166/h for the tractor-drawn spreader with broadcast application on the 175-cow herd to more than $586/h with the 1400-cow herd using two tractor-drawn spreaders for hauling distances less than 4.8 km (3 mi) and one tractor-drawn spreader with two nurse tanks of equivalent size for over-the-road transport (Table 3j). On a per liter (gallon) basis the cost for agitation, pumping, transport and broadcast application ranged from 0.33 ¢/L (1.24¢/gal) when using two tractor-drawn spreaders with an average hauling distance of 3.2 km, (2 mi) with the 700-cow herd to 0.53 ¢/L (2.02 ¢/gal) when using nurse trucks and hauling up to 4.8 km (3 mi) with the 1,400-cow herd. Additional costs for tillage incorporation of manure with a tandem disk ranged from 0.03-0.06 ¢/L (0.11 to 0.25¢/gal). Manure injection increased agitation, pumping, transport and land application costs by 15% for the 700-cow dairy using two sets of tractor-drawn manure spreaders.

3.7.3 Manure pumping and land application on four 1,400 cow dairies

Machinery sets and an average transport distance were varied for four representative 1400-cow dairies to evaluate the cost for labor and cost for manure agitation, pumping, transport and land application (Table 3k). The average transport distance for farms 1 and 2 was 4 km (2.5 mi). Farm 1 used four 34,065 L (9,000 gal) tractor-drawn spreaders working in parallel. Farm 2 used two 34,065 L (9,000 gal) tractor-drawn spreaders for distances less than 4.8 km (3 mi), and a 34,065 L (9,000 gal) tractor-drawn spreader with two 34,065 L (9,000 gal) nurse tanks for distances greater than 4.8 km (3 mi). The average transport distance was increased by 50% to 6.4 km (4 mi) for farms 3 and 4. Similar to farm 2, farm 3 used two 34,065 L (9,000 gal) tractor-drawn spreaders for distances less than 4.8 km (3 mi), and a 34,065 L (9,000 gal) tractor-drawn spreader with two 34,065 L (9,000 gal) nurse tanks for distances greater than 4.8 km (3 mi). Farm 4 used two 34,065 L (9,000 gal) tractor-drawn spreaders with two 34,065 L (9,000 gal) nurse tanks. A list of farm parameters and results are provided in Table 3k.

Table 3k. 1,400-cow dairy farm characteristics and equipment used for broadcast and injection application

	Farm 1	Farm 2	Farm 3	Farm 4
Manure volume, L (gal)	46,216,155 (12,210,345)	46,216,155 (12,210,345)	46,216,155 (12,210,345)	46,216,155 (12,210,345)
Hauling distance, km (mi)				
Field Zone 1: Corn silage	1.6 (1.0)	1.6 (1.0)	2.4 (1.5)	2.4 (1.5)
Field Zone 2: Corn silage	2.4 (1.5)	2.4 (1.5)	3.2 (2.0)	3.2 (2.0)
Field Zone 3: Corn grain	5.0 (3.1)	5.0 (3.1)	7.6 (4.7)	7.6 (4.7)
Field Zone 4: Corn grain	6.8 (4.2)	6.8 (4.2)	10.1 (6.3)	10.1 (6.3)
Average hauling	4.0 (2.5)	4.0 (2.5)	6.4 (4.0)	6.4 (4.0)
Broadcast Application Equipment				
Machinery set	4 sets - tractor-drawn spreader	2 tractor-drawn spreaders <3 mi, 1 spreader and 2 nurse tanks >3 mi	2 tractor-drawn spreaders <3 mi, 1 spreader and 2 nurse tanks >3 mi	2 sets- tractor-drawn spreaders with 2 nurse tanks
Pumping and agitation				
Tractor, pto-kW (pto-hp)	127 (170)	127 (170)	127 (170)	127 (170)
Pump (size)	2 Large lagoon pump	2 Large lagoon pump	2 Large lagoon pump	2 Large lagoon pump
Manure Hauling				
Spreader tractor,pto-kW (pto-hp)	4-179 (4-240)	2-179 (2-240)	2-179 (2-240)	2-179 (2-240)
Spreader tank, L (gal)	4-34,065 (4-9,000)	2-34,065 (2-9,000)	2-34,065 (2-9,000)	2-34,065 (2-9,000)
Truck , pto-kW (pto-hp)	--	2-298 (2-400)	2-298 (2-400)	4-298 (4-400)
Nurse tank, L (gal)	--	2-34,065 (2-9,000)	2-34,065 (2-9,000)	4-34,065 (4-9,000)
Incorporation				
Tractor for tillage, pto-kW (pto-hp)	134 (180)	134 (180)	134 (180)	134 (180)
Tillage equipment m (ft)	9.8 (32) tandem disk	9.8 (32) tandem disk	9.8 (32) tandem disk	9.8 (32) tandem disk
Results				
Hauling rate, L/hr (gal/hr)				
Field zone 4: corn silage	323,477 (85,463)	161,738 (42,731)	142,235 (37,579)	220,201 (58,177)
Field zone 3: corn silage	284,470 (75,157)	142,235 (37,579)	125,083 (33,047)	220,201 (58,177)

Table 3k cont.

Field zone 2: corn grain	188,562 (49,818)	102,831(27,168)	87,782 (23,192)	175,563 (46,384)
Field zone 1: corn grain	154,947 (40,937)	92,231 (24,368)	74,934 (19,798)	149,868 (39,595)
Average hauling rate	237,864 (62,844)	124,759 (32,961)	107,508 (28,404)	191,459 (50,584)
Labor				
Pumping, agitation, transport and application, hours (days)	224 (22.4)	407 (34.6)	482 (41.3)	255 (12.7)
Tillage incorporation, hours (days)	136 (13.6)	136 (13.6)	136 (13.6)	136 (13.6)
Cost				
Agitation, pumping, transport, application; $/h	787.71	586.36	578.57	796.76
¢/L (¢/gal)	0.35 (1.31)	0.40 (1.51)	0.47 (1.79)	0.39 (1.49)
$/ha ($/acre)	29.88 (73.84)	36.24 (89.55)	42.08 (103.97)	34.23 (84.59)
Tillage incorporation, $/h	99.71	99.71	99.71	99.71
¢/L (¢/gal)	0.03 (0.11)	0.03 (0.11)	0.03 (0.11)	0.03 (0.11)
$/ha ($/acre)	2.72 (6.71)	2.72 (6.71)	2.72 (6.71)	2.72 (6.71)
Total cost ¢/L (¢/gal)	0.38 (1.42)	0.43 (1.62)	0.50 (1.90)	0.42 (1.49)
Nutrient credit, ¢/L (¢/gal)	-0.64 (-2.41)	-0.64 (-2.41)	-0.64 (-2.41)	-0.64 (-2.41)
Net return over hauling costs, ¢/L (¢/gal)	0.26 (0.99)	0.21 (0.79)	0.14 (0.51)	0.22 (0.81)
Injection Application Equipment				
Spreader Tractor, pto-kW (pto-hp)	194 (260)	2-194 (2-260)	2-194 (2-260)	2-194 (2-260)
Spreader tank, L (gal)	4-34,065 (4-9,000)	2-34,065 (2-9,000)	2-34,065 (2-9,000)	2-34,065 (2-9,000)
Truck , pto-kW (pto-hp)	-	2-298 (2-400)	2-298 (2-400)	4-298 (2-400)
Nurse tank, L (gal)	-	2-34,065 (2-9,000)	2-34,065 (2-9,000)	4-34,065 (2-9,000)
Results				
Hauling rate, L/hr (gal/hr)				
Field zone 4: corn silage	264,404 (69,856)	134,296 (35,481)	121,516 (32,105)	186,028 (49,149)
Field zone 3: corn silage	235,328 (62,174)	121,516 (32,105)	109,952 (29,049)	186,028 (49,149)
Field zone 2: corn grain	162,094 (42,825)	100,843 (26,643)	86,484 (22,849)	172,969 (45,698)

Table 3k cont.

Field zone 1: corn grain	137,139 (36,232)	90,737 (23,973)	74,170 (19,596)	148,341 (39,192)
Average hauling rate	199,741 (52,772)	111,848 (29,550)	98,031 (25,900)	173,341 (45,797)
Labor				
Pumping, agitation, transport and application, hours (days)	261 (26.1)	435 (36.3)	508 (42.8)	273 (27.3)
Cost	Farm 1	Farm 2	Farm 3	Farm 4
Agitation, pumping, transport, application; $/h	809.83	605.43	597.75	808.91
¢/L (¢/gal)	0.55 (1.54)	0.46 (1.73)	0.52 (1.79)	0.42 (1.60)
$/ha ($/acre)	35.60 (87.98)	38.70 (95.59)	45.48 (112.38)	37.11 (91.69)
Nutrient credit, ¢/L (¢/gal)	-0.70 (-2.65)	-0.70 (-2.65)	-0.70 (-2.65)	-0.70 (-2.65)
Net return over hauling costs, ¢/L (¢/gal)	0.15 (1.11)	0.24(0.92)	0.12 (0.69)	0.28 (1.05)

3.7.4. Broadcast application for four 1,400-cow dairies

Selecting two tractor-drawn spreaders for transporting less than 4.8 km (3 mi) and a tractor-drawn spreader with 2 nurse tanks for distances greater than 4.8 km (3 mi; farm 2) increased labor hours by 82% compared to farm 1 (4 tractor-drawn spreaders). Forty percent of the crop area for Farm 2 was within a 4.8 km (3 mi) hauling distance which resulted in an average hauling rate of 64,609 L/hr (40,155 gal/hr) to complete manure agitation, pumping, transport and spreading within 122 hours. The remaining 60% of the crop area was located at hauling distances greater than 4.8 km (3 mi) which decreased the average hauling rate to 43,070 L/hr (25,768 gal/hr) and required 285 hours to complete manure agitation, pumping, transport and spreading. Farm 2 had lower hourly costs compared to Farm 1, but the increased hours required for further hauling distances resulted in 15% higher ¢/L (¢/gal) costs.

When transporting manure greater than 4.8 km (3 mi), systems using nurse trucks are generally more efficient than tractor drawn spreader tanks of the same volume (fig 3b). Sixty percent of the acreage on farms 1-4 required hauling distances greater than 4.8 km (3 mi). Farm 2 and 3 used equivalent machinery sets to transport and spread manure. Increasing the hauling distances to all four field zones by 50% resulted in farm 3. The increased hauling distances using equivalent equipment increased hourly labor requirements by 18.2 % and manure pumping, agitation, transport and spreading costs by 18.6% for broadcast application.

Hauling distances for farm 4 were equivalent to those used by farm 3. Farm 4 used two tractor-drawn spreaders, each with two nurse tanks in parallel, rather than a split system at 4.8 km (3 mi) used by farm 3. Labor requirements for farm 4 were 255 hours, 46% lower than farm 3. Using two sets of tractor-drawn spreaders with two nurse tanks in parallel allows for two tractors to spread manure, while four nurse trucks are transporting manure over-the-road to the tractor in the field with limited to no idle time. Farm 3 used 2 tractor-drawn spreaders for manure application within 4.8 km (3 mi) and only 1 tractor-drawn spreader with 2 nurse trucks for over-the-road transport for hauling distances greater than 4.8 km (3 mi) which increases potential idle time since 60% of the acreage available for manure application is at hauling distances greater than 4.8 km (3 mi).

Hauling distance has an impact on the timeliness of manure agitation, pumping, transport and spreading based on the machinery set chosen. Compared to Farm 1, labor for Farm 4 increased by 14% but hauling costs decreased 20% with the truck-drawn nurse tank-based systems even though the average transport distance increased by 50%. This illustrates the advantage of nurse trucks for over-the-road transport compared to tractor-drawn spreaders when the hauling distance exceeds 4.8 km (3 mi) as was shown earlier in Figure 2.

Crediting manure nutrient value allows the farmer to reduce commercial fertilizer purchase and reduce total manure hauling system cost. Fertilizer recommendations are based on crop nutrient removal requirements for crop yield as shown in Table 3g. The nutrient value of manure was calculated based on the soil test restuls as outlined by the Tri-state fertilizer recommendations as shown previously in Table 3e. If crop soil test results indicate nutrient deficit soil ("build-up zone"), additional nutrients above crop removal needs can be applied up to nitrogen removal rates for the crop. Crop soil test results in the "maintenance zone" indicate that adequate nutrients are available in the soil for the crop to obtain an optimal yield. At a "maintenance zone" soil test result level, the farmer must apply manure nutrients at the P_2O_5 removal needs of the crop. Over-application of the crop nutrient needs will lead to increased nutrients in the soil not used by the crop, and require a nutrient "draw-down" as more nutrients are applied over time. Soil test results for farm 1-4 were assumed to be in the "maintenance" zone as shown in table 3g. Therefore, manure application rates must not exceed the P_2O_5 nutrient removal for the crop. MANURE$HAUL does not limit the manure application rate based on crop nutrient removal rates and soil test results. Rather, MANURE$HAUL assigns a N, P_2O_5, and K_2O nutrient value to manure up to the crop P_2O_5 nutrient removal for soil test results in the "maintenance zone" (Table 3e). Table 12 lists the fertilizer recommendations for farm 1-4 based on nutrient removal for corn grain and corn silage. Manure production for farm 1-4 was 46,216,155 L (12,210,345 gal) of manure with 6.24

kg/1000 L (52 lbs/1000 gal) of N, 3.01 kg/1000L (25 lbs/1000 gal) P_2O_5, and 3.97 kg/1000L (33 lbs/1000 gal) K_2O. Manure nutrients applied are listed in Table 31 and compared to the fertilizer recommendations for corn grain and corn silage. N removal needs were not met with the manure application rate; therefore supplement commercial N fertilizer will be needed for optimal crop yields. $P_2O_5$and K_2O applied through manure application exceeded the crop removal needs. Since soil test results were in the "maintenance zone" a nutrient value of manure was assigned to N, P_2O_5, and K_2O up to the crop P_2O_5nutrient removal as listed in Table 31. This resulted in a nutrient value of manure of 0.63 ¢/L (2.41 ¢/gal) for broadcast incorporation within one day of manure application. Injection application reduced N losses to increase manure nutrients applied to 105 kg/ha (94 lbs/ac). Injection incorporation resulted in 0.70 ¢/L (2.65 ¢/gal) nutrient value of manure.

Table 3l. Fertilizer recommendations, manure nutrients applied, and nutrient credit values for broadcast application

	Fertilizer recommendation[1]			Nutrient Credits[3]	
	Corn grain	Corn silage	Manure Nutrients applied[2]	Corn grain	Corn silage
N, kg/ha (lbs/acre)	131 (117)	158 (141)	80 (72)	80 (72)	80 (72)
P_2O_5, kg/ha (lbs/acre)	54 (48)	56 (50)	122 (109)	54 (48)	56 (50)
K_2O, kg/ha (lbs/acre)	39 (35)	154 (120)	196 (175)	39 (35)	154 (120)

[1] Estimated in Table 3g

[2] Manure nutrient content presented in Table 3h.

[3] Nutrient credits are calculated up to crop removal for P2O5 and K2O since soil test results are in the maintenance zone as shown in Table 3g.

3.7.5 Subsurface injection application results for four 1,400-cow dairy farms

Manure injection increased labor requirements for farms 1-4 (Table 3k). Using four sets of tractor-drawn spreaders for subsurface injection application (farm 1) with an average hauling distance of 4 km (2.5 mi) increased labor requirements by 17% compared to broadcast application with an 18% increase in manure agitation, pumping, transport and spreading costs. However, injection application resulted in a nutrient value of manure of 0.70 ¢/L (2.65 ¢/gal) compared to 0.63 ¢/L (2.41 ¢/gal) for broadcast application. Applying the nutrient value of manure resulted in manure agitation, pumping, transport and spreading costs 12% higher for subsurface injection compared to broadcast application for farm 1. Manure hauling costs decreased by 6% when a nutrient value for manure was assigned for farm 1.

Manure agitation, pumping, transport, and spreading cost was 0.46 ¢/L (1.73 ¢/gal) and 0.52 ¢/L (1.96 ¢/gal) for farm 2 and 3 using two tractor-drawn spreaders for hauling distances less than 4.8 km (3 mi) and two truck-drawn nurse tanks for over-the-road transport to a tractor-drawn spreader in the field using injection application for hauling distances greater than 4.8 km (3 mi). Crediting the nutrient value of manure resulted in a net return over manure agitation, pumping, transport, and application costs of 0.24 ¢/L (0.92 ¢/gal) for farm 1 and 0.12 ¢/L (0.69 ¢/gal) for farm 2, which was 16 and 36% higher than that recognized for broadcast application, respectively .

Farm 4 using two sets of 2 truck-drawn nurse tanks for over-the-road transport to a tractor-drawn spreader in the field in parallel had the highest net return over hauling costs of 0.28 ¢/L (1.05 ¢/gal) for injection application with the second lowest labor requirement (25.5 days) across the four 1,400-cow dairy farms.

The return over hauling cost was positive for farms 1-4 indicating a cost savings when considering the fertilizer value of manure for both injection and broadcast application. Injection application allows farmers to decrease nutrient losses, which are valued at fertilizer prices. However, injection application increases the labor requirements needed for manure agitation, pumping, transport and spreading. Farmers must evaluate the trade-off for increased labor requirements and costs for injection application compared to broadcast application. If manure application will cause delays in crop tillage and planting, a farmer may want to evaluate the use of a different manure hauling system to better accommodate the needs of their farm.

3.7.6 Return on fertilizer value of manure

The fertilizer value of manure depends on the manure application method used (subsurface injection, broadcast with incorporation, and broadcast) as well as the soil test results. Using the results from the 1,400-cow dairy as an example, manure is valued at 1.3 ¢/L (4.8 ¢/gal) based on manure analysis. If the farmer uses subsurface injection and soil test results are in the "build-up zone" the farmer will assign a nutrient value equivalent to the manure analysis results (Table 3m). Using broadcast incorporation resulted in 70% retention of nitrogen resulting in a 4% loss of manure nutrient value compared to subsurface injection whereas failure to incorporate manure resulted in a 15% loss in nutrient value compared to subsurface injection for manure applied on soil in the "build-up zone".

Nutrient value of manure is lower for soil test results in the maintenance zone since soil tests results are at a level for optimal crop yield. Therefore only nutrients applied up to P_2O_5 crop removal needs are used to calculate the nutrient value of manure. Applying manure at levels greater than P_2O_5 crop removal needs causes nutrient build-up which may lead to the farmer limiting manure application at later dates to "draw-down" soil nutrient levels. Broadcast with incorporation and broadcast application resulted in a nutrient values of manure 9% and 18% lower than subsurface injection, respectively.

If soil test results are in the "draw-down zone" the nutrient value of manure is zero. Applying manure on soil in the "draw-down zone" adds additional nutrients above recommended levels which further exacerbates the nutrient problem in the soil. Assigning a nutrient value of zero to manure demonstrates that for a farmer to fully recognize the nutrient value of manure, it must be applied following recommended fertilizer guidelines.

Table 3m. Nutrient value of manure for injection, broadcast with incorporation, and broadcast application as a function of soil test results

Application Method	N-Nutrient retention	Soil test result zone Build-up	 Maintenance	 Draw-down
			¢/L (¢/gal)	
Injection	100%	1.27 (4.8)	0.70 (2.65)	0.0 (0.0)
Broadcast with incorporation	70%	1.22 (4.6)	0.64 (2.41)	0.0 (0.0)
Broadcast	10%	1.08 (4.1)	0.51 (1.94)	0.0 (0.0)

3.8 Model Validation

The ownership and operating costs calculated by MANURE$HAUL were compared with costs reported by two Michigan livestock producers. Each farm used a tractor-drawn spreader tank. One cooperator was a swine producer handling about 22.7 million L (6 million gallons) of manure per year. The other cooperator was a crop producer who hauled approximately 11.4 million L (3 million gal) per year from a nearby dairy. Each of the livestock managers had current records of costs and labor requirements for their manure hauling operations.

3.8.1 Swine producer

The swine producer raised 9,600 finishing pigs to 136 kg (300 lbs) each year. The volume of manure hauled in 2008, 22,839,670 L (6,034,259 gal) was within one percent of that calculated by MANURE$HAUL (23,740,125 L (6,272,160 gal)). The swine manure was stored at two locations and an average hauling distance from each storage pit was one mi. Manure was transported and applied with a 205 pto-kW (275 pto-pto-hp) tractor with a 37,850 L (10,000 gal) tank and injected with a 6-point injector. The fuel price in 2008 was $0.85/L ($3.20/gal).

MANURE$HAUL calculated a hauling cost of 0.29 ¢/L (1.12 ¢/gal) for agitation, pumping, transport and land application using the default values for depreciation (10-yr, straight line) and repair and maintenance costs based on accumulated use. The producer calculated his cost as 0.32 ¢/L (1.23 ¢/gal). Annual repair and maintenance cost was 15% of the equipment purchase price, and he used a 5-yr rather than a 10-yr depreciation schedule. Manure pumping and agitating time was estimated by the producer to be 25% of the total hauling time and was valued at $17/h of total hauling time (based on $68/h of continuous use). Labor was valued at $15/h.

A change in the depreciation schedule from 10 to 5 years increased the MANURE$HAUL calculated hauling cost by 16%. Increasing the labor wage rate from $12 to $15/h increased the calculated hauling costs by 1%. Estimating the annual repair and maintenance costs as 15% of the list price rather than basing the cost on accumulated use lowered the MANURE$HAUL calculated cost by 3%. Decreasing the hourly charge on the agitation and pump tractor decreased hauling costs by 1.8%. When the default and calculated values for depreciation, repair and maintenance, labor wage rate and pump/agitation in MANURE$HAUL were aligned with those of the swine producer, MANURE$HAUL calculated a cost for pumping, agitation, transport and land application of 0.31 ¢/L (1.20 ¢/gal) which was within 1% of the cost reported by the swine producer 0.32 ¢/L (1.23 ¢/gal)..

3.8.2 Cash crop producer

The cash-crop farmer had an agreement with a neighboring dairy farmer to take 11.4 million L (3 million gal) of manure as a soil amendment and source of crop nutrients. The dairy farmer provided the agitation and pumping and the crop farmer provided a 179 pto-kW (240 pto-pto-hp) tractor and 26,495 L (7,000 gal) tractor-drawn spreader for broadcast application with tillage incorporation. The average hauling distance was 4.8 km (3 mi). Costs for tillage incorporation of the manure were allocated to the cropping program and were not included in the calculation of hourly costs. Fuel costs in 2008 were $0.86/L ($3.25/gal). Labor was valued at $20/h. When the labor and fuel costs reported by the crop producer were used with MANURE$HAUL the calculated hauling cost was $156/h. The crop farmer's reported hourly cost for transport and broadcast application was $155/hr.

When the standard default values in MANURE$HAUL were adjusted to reflect the specific parameters reported by two Michigan livestock and crop producers, MANURE$HAUL cost estimates were within 1% of those reported by the cooperating producers. MANURE$HAUL calculated costs were within 9% of the reported costs when using the standard default values. MANURE$HAUL is a decision support tool suitable for estimating costs for a specific farm or comparing alternative manure transport and land application methods across a range of transport distances.

3.9 Hauling cost model

Manure managers may find it useful to estimate manure hauling costs in aggregate form as a base cost plus a mileage differential. Leibold and Olsen (2007) reported a base cost of 0.26 ¢/L (1 ¢/gal) plus a mileage differential of 0.26 ¢/L-km

.(0.1¢/gal-mi). MANURE$HAUL was used to estimate costs for agitation, pumping, transport and land application for six machinery sets using top-loading tank spreaders: (1) standard tractor-drawn spreader, (2) high-speed tractor-drawn spreader, (3) truck-mounted tank spreader, (4) truck-drawn tank spreader, (5) two nurse tanks for over-the road transport to a tractor-drawn spreader in the field with the nurse tank volume equal to spreader tank volume, and (6) two nurse tanks for over-the road transport to a tractor-drawn spreader in the field with the nurse tank volume two times the spreader tank volume. Cost estimates for subsurface injection were included with tractor-drawn tank spreaders, and estimates for tillage incorporation with a tractor and tandem disk were included with surface broadcast systems.

The hauling cost (¢/L, ¢/gal) was calculated for each machinery set such that the manure was applied within 175 hours with transport distances ranging from 0.16 to 16 km (0.1 to 10 mi). A multiple linear regression of the calculated costs was completed with cost as the dependant variable and transport distance and tank volume as the independent variables. A linear relationship among variables was achieved by regressing distance and volume on the reciprocal of the square root of the calculated cost. The proposed equation is a composite of machinery system-specific parameters and coefficients:

$$C = ((A+BD+EV)^2)^{-1} \qquad (3)$$

Where:

C is cost for manure agitation, pumping, transport or application; ¢/L (¢/gal)

A, B and E are dimensionless machinery system-specific regression coefficients (Table 3n)

D is transport distance; 0.16 to 16 km (0.1 to 10 mi)

V is spreader tank volume; 9464 to 37850 L (2500-10 000 gal).

3.9.1 Hauling cost coefficients

Representative machinery and labor costs were used to model the cost of manure agitation, pumping, transport and land application for tank spreader systems as a function of spreader tank volume and transport distance. Simulated hauling rates were fit to a general model to develop machinery system-specific coefficients to predict costs for tractor-drawn and truck-drawn spreader tanks, and hauling systems using truck-drawn nurse tanks for over-the-road transport to tractor-drawn spreader tanks for field spreading. The machinery-system specific coefficients are presented in a reference table and can be used to estimate liquid manure hauling costs over a range of tank volume and travel distance (Table 3n).

The proposed equation and machinery-specific coefficients is a reliable predictor of the calculated costs. The correlation coefficients (R^2) of the predicted costs ranged from 96.8 to 99.7% (Table 3n). Costs for two tractor-drawn (22710 L, 6000 gal) top-loading spreader tanks were calculated for transport distances ranging from 0.16 to 6.4 km (0.1to 4 mi). Calculated costs for a standard tractor with slurry injection including agitation and pumping ranged from 0.26 to 0.63 ¢/L (0.98 to 2.39 ¢/gal) over the 6.4 km (4 mi) hauling distance (Fig. 3d). Predicted costs ranged from 0.27 to 0.67 ¢/L (1.02 to 2.53 ¢/gal). Lower costs were calculated for a high-speed tractor with broadcast application. In each case the predicted costs provided a close approximation of the calculated costs.

The proposed model with machinery-specific coefficients provides a convenient option for comparing alternative hauling systems. Representative costs can be predicted for commonly used spreader tank systems with tank volumes ranging from 9,460 to 37,850 L (2,500 to 10,000 gal) and hauling distances of 0.16 to 16 km (0.1 to 10 mi). Scarborough et al. (1978) evaluated spreader tank costs and reported that selection of a larger than optimal spreader tank was generally more economical than a smaller than optimal tank, and optimal tank volume increased as transport distance increased. The proposed model will facilitate such detailed comparisons and optimization procedures.

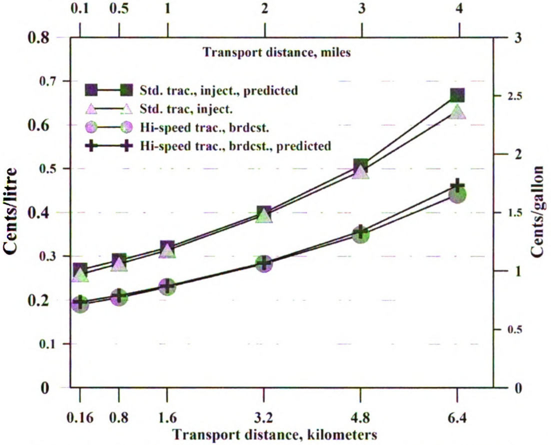

Figure 3c. Calculated manure agitation, pumping, transport and spreading versus predicted costs using machinery specific coefficients

Table 3n. Liquid manure machinery system-specific regression coefficients for estimating cost for agitation, pumping, transport and land application.

	Cost coefficients			
Machinery Set	A	B	E	R^2
Tractor-drawn tank spreaders				
Standard tractor, A,P,T, S				
Broadcast, ¢/L	2.20	-0.138	0.000002	99.2
¢/gal	(1.13)	(-0.114)	(0.000004)	(99.2)
Injection, ¢/L	0.964	-0.0927	0.000006	98.7
¢/gal	(1.87)	(-0.112)	(0.000003)	(98.7)
Standard tractor, T,S				
Broadcast, ¢/L	2.62	-0.162	-0.000004	99.1
¢/gal	(1.35)	(-0.134)	(-0.000008)	(99.1)
Injection, ¢/L	1.11	-0.106	-0.000001	98.8
¢/gal	(2.16)	(-0.128)	(-0.000007)	(98.8)
Standard tractor, T,S, I				
Broadcast, ¢/L	2.28	-0.123	-0.000003	99.3
¢/gal	(1.17)	(-0.101)	-0.000006	(99.3)
Standard tractor, A,P				
Broadcast, ¢/L	3.73	-0.242	0.000052	98.6
¢/gal	(1.92)	(-0.200)	(0.000101)	(98.6)
Injection, ¢/L	1.82	-0.179	0.000091	98.2
¢/gal	(3.54)	(-0.217)	(0.000047)	(98.2)
High-speed tractor, A,P,T,S				
Broadcast, ¢/L	1.16	-0.104	0.000002	99.1
¢/gal	(2.20)	(-0.138)	(0.000002)	99.1
Injection, ¢/L	0.973	-0.0801	0.000004	97.8
¢/gal	(1.89)	(-0.097)	(0.000002)	(97.8)
High-speed tractor, T,S				
Broadcast, ¢/L	1.38	-0.122	-0.000010	99.0
¢/gal	(2.62)	(-0.162)	(-0.000004)	(99.0)
Injection, ¢/L	1.12	-0.0915	-0.000004	98.2
¢/gal	(2.18)	(-0.111)	(-0.000002)	(98.2)
High-speed tractor, T,S,I				
Broadcast, ¢/L	1.19	-0.0901	-0.000006	99.1
¢/gal	(2.27)	(-0.123)	(-0.000008)	(99.1)
High-speed tractor, A,P				
Broadcast, ¢/L	1.94	-0.175	0.000103	98.9
¢/gal	(3.74)	(-0.242)	(0.00052)	(98.9)
Injection, ¢/L	1.82	-0.152	0.000089	97.8
¢/gal	(3.54)	(-0.184)	(0.000046)	(97.8)

Table 3n continued

Machinery Set	A	B	E	R^2
Tractor-drawn/nurse tank systems				
Spreader = 1X nurse tank, A,P,T,S				
Broadcast, ¢/L	0.665	-0.0312	0.000025	99.3
¢/gal	(1.293)	(-0.0375)	(0.000013)	(99.3)
Injection, ¢/L	0.620	-0.0279	0.000025	99.5
¢/gal	(1.208)	(-0.0339)	(0.000013)	(99.5)
Spreader = 1X nurse tank, T,S				
Broadcast, ¢/L	0.727	-0.0351	0.000027	99.2
¢/gal	(1.418)	(-0.0426)	(0.000014)	(99.2)
Injection, ¢/L	0.677	-0.0316	0.000027	99.5
¢/gal	(1.318)	(-0.0381)	(0.000014)	(99.5)
Spreader = 1X nurse tank, T,S,I				
Broadcast, ¢/L	0.691	-0.0307	0.000023	99.6
¢/gal	(1.346)	(-0.037)	(0.000012)	(99.6)
Spreader = 1X nurse tank, A,P				
Broadcast, ¢/L	1.61	-0.0577	0.000062	99.5
¢/gal	(3.14)	(-0.070)	(0.000032)	(99.5)
Injection, ¢/L	1.56	-0.0534	0.000064	99.5
¢/gal	(3.03)	(-0.064)	(0.000033)	(99.5)
Nurse tank = 2X spreader, A,P,T,S				
Broadcast, ¢/L	0.666	-0.0259	0.000046	99.6
¢/gal	(1.300)	(-0.0314)	(0.000023)	(99.6)
Injection, ¢/L	0.621	-0.0228	0.000046	99.7
¢/gal	(1.211)	(-0.0281)	(0.000024)	(99.7)
Nurse tank = 2X spreader, T,S				
Broadcast, ¢/L	0.700	-0.0276	0.000048	99.4
¢/gal	(1.362)	(-0.0335)	(0.000025)	(99.4)
Injection, ¢/L	0.650	-0.0243	0.000048	99.7
¢/gal	(1.270)	(-0.0294)	(0.000024)	(99.7)
Nurse tank = 2X spreader, T,S, I				
Broadcast, ¢/L	0.669	-0.0241	0.000042	99.7
¢/gal	(1.300)	(-0.0291)	(0.00022)	(99.7)
Nurse tank = 2X spreader, A,P				
Broadcast, ¢/L	2.07	-0.0592	0.000161	97.1
¢/gal	(4.037)	(-0.0712)	(0.000083)	(97.1)
Injection, ¢/L	2.14	-0.0633	0.000149	98.8
¢/gal	(4.16)	(-0.0761)	(0.000076)	(98.7)

Table 3n continued

Machinery Set		A	B	E	R^2
Truck-mounted/drawn systems					
Truck-mounted, A,P,T,S					
	Broadcast, ¢/L	0.878	-0.0513	0.000053	97.3
	¢/gal	(1.710)	(-0.0623)	(0.000027)	(97.3)
Truck-mounted, T,S					
	Broadcast, ¢/L	1.01	-0.0613	0.00006	96.9
	¢/gal	(1.97)	(-0.0741)	(0.000031)	(96.9)
Truck-mounted, T,S,I					
	Broadcast, ¢/L	0.923	-0.0467	0.000045	98.0
	¢/gal	(1.797)	(-0.0567)	(0.00023)	(98.0)
Truck-mounted, A,P					
	Broadcast, ¢/L	1.73	-0.0904	0.000115	96.8
	¢/gal	(3.363)	(-0.109)	(0.00060)	(96.8)
Semi-tractor drawn, A,P,T,S					
	Broadcast, ¢/L	0.987	-0.0524	0.000034	97.6
	¢/gal	(1.92)	(-0.063)	(0.000018)	(97.6)
Semi-tractor drawn, T,S,					
	Broadcast, ¢/L	1.15	-0.0634	0.000038	97.4
	¢/gal	(2.23)	(-0.0768)	(0.00002)	(97.4)
Semi-tractor drawn, T,S,I					
	Broadcast, ¢/L	1.02	-0.0458	0.000028	98.5
	¢/gal	(1.98)	(-0.0554)	(0.000014)	(98.5)
Semi-tractor drawn, A,P					
	Broadcast, ¢/L	1.92	-0.0879	0.000079	97.8
	¢/gal	(3.73)	(-0.1063)	(0.000041)	(97.8)

3.10 Conclusion

MANURE$HAUL provides a flexible decision tool for comparing cost-effective alternative manure hauling systems. MANURE$HAUL provides an accurate estimate of time needed for manure pumping, transport, and land application as a function of hauling distance, spreader capacity, manure equipment cost, labor, and nutrient value of manure. MANURE$HAUL was used to estimate costs for agitation, pumping, transport and land application for two machinery sets using top-loading tank spreaders: (1) tractor-drawn spreader and (2) two nurse tanks for over-the road transport to a tractor-drawn spreader in the field with the nurse tank volume equal to spreader tank volume for a 175-, 350-, 700-, and 1,400-cow dairy. Manure hauling cost estimates using MANURE$HAUL for the representative dairy farms illustrated the following:

- Ownership and operating costs for manure agitation, pumping, transport and land application ranged from $166/hr for a tractor-drawn spreader with broadcast application on a 175-cow dairy to more than $586/hr with the 1,400-cow dairy using two large tractor-drawn spreaders and two nurse trucks.
- Manure tillage costs ranged from $99/hr for the 1,400-cow dairy to $134/hr for the 350-cow dairy. Manure tillage costs were dependent on the acreage used for manure application and equipment size.
- Ownership and operating costs for manure agitation, pumping, transport and land application ranged from 0.40-0.52¢/L (1.54-1.96 ¢/gal) for injection application, which was 7-18% higher than broadcast application.
- Using two sets of two nurse tanks for over-the road transport to a tractor-drawn spreader in the field with an average hauling distance of 6.4 km (4 mi) for the 1,400-cow dairy resulted in a 14% increase in hauling time compared to using 4 tractor-drawn spreaders with an average hauling distance of 4.8 km (3 mi).
- Labor requirements for subsurface injection increased by 14%, 18.5%, 19.3%, and 6.8% for the 175-, 350-, 700-, and 1,400-cow herds, respectively, compared to a broadcast application
- The nutrient value of manure using subsurface injection on soil in the "maintenance zone" was 0.70 ¢/L (2.65 ¢/gal) compared to 0.63¢/L (2.41 ¢/gal)

for broadcast application with incorporation and 0.51¢/L (1.94 ¢/gal) for broadcast application.

- The manure hauling cost was most sensitive to tank spreader capacity and manure hauling distance. Increasing hauling distance by 50% for a 1,400-cow dairy using two 34,065 L (9,000 gal) tractor drawn spreaders for hauling distances less than 4.8 km (3 mi) and two 34,065 L (9,000 gal) truck-drawn nurse tanks for hauling distances greater than 4.8 km (3 mi) increased labor requirements by 18.2% and manure pumping, agitation, transport and spreading costs by 18.6% for broadcast application.

- Machinery specific coefficients were estimated for commonly used tank spreader systems as a function of tank volume and transport distance. Machinery specific coefficients are presented in a convenient reference table.

REFERENCES

ASAE Standards, 50th ed. 2003. D497.4: Agricultural Machinery Management Data. St. Joseph, Mich.: ASAE.

ASAE Standards, 53rd ed. 2006. EP496.3: Agricultural Machinery Management Data. St. Joseph, Mich.: ASAE.

Black, J.B., 2008. Working Paper. Tart Cherry Production.

Borton, L.R., C.A. Rotz, H.L. Person, T.M. Harrigan, and W.G. Bickert. 1995. Simulation to Evaluate Dairy Manure Systems. *Applied Eng. Agric.* 11(2):301-310.

Case-IH. "Machine Builder." Accessed October 2008 and February 2009: http://caseih.cnhbuilder.com

Harrigan, T.M. 1997. Manure hauling rate of spreader tank systems. *Applied Eng. Agric.* 13(4):465-472.

Harrigan, T.M. 2001. Manure Transport Rates and Land Application Costs for Tank Spreader Systems. Michigan State University Extension Bulletin E-2767. East Lansing, MI.

Harrigan, T.M, W.G. Bickert, and C.A. Rotz. 1996. Simulation of dairy manure management and cropping systems. ASAE Paper No. 95-4509. St. Joseph, MI: ASAE.

Harrigan, T.M. 2009. Liquid Manure Hauling Capacity of Custom Applicators using Tank Spreader Systems in the Great Lakes Region. *In Submission.*

Iowa State University. 2005. Machinery Management—Estimating Farm Machinery Costs. Iowa State University Extension Bulletin PM 710. Ames, Iowa.

IRON Solutions. 2006. Farm Equipment Official Guide. Fenton, Missouri: IRON Solutions Equipment Market Intelligence.

Jacobs, L.W. 1995a. Manure Management—Utilization of Animal Manure for Crop Production. Part I. Management of Manure Nutrients and Water Quality. Michigan State University Extension Bulletin MM-1. East Lansing, MI.

Jacbos, L.W. 1995b. Manure Management—Utilization of Animal Manure for Crop Production. Part II. Manure Application to Cropland. Michigan State University Extension Bulletin MM-2. East Lansing, MI.

John Deere. "Build Your Own John Deere." Accessed October 2008 and February 2009: http://configurator.deere.com

Koehler, B., B. Lazarus, and W. Meland. 2009. "What's Manure Worth" Spreadsheet. University of Minnesota, St. Paul, Minnesota. Available at: http://www.apec.umn.edu/faculty/wlazarus/interests_manureworth.html Accessed on 4 May 2009.

Koelsch, R., G. Erickson, and R. Massey. 2007. "Feed Nutrient Planning Economics (FNMP$)." University of Nebraska-Lincoln, Lincoln, Nebraska. Available at: http://manure.unl.edu/computer.html Accessed on 9 February 2009.

Leibold, K., and T. Olsen. 2007. "Value of Manure Nutrients" Spreadsheet. Iowa State University, Ames, Iowa. Available at: http://www.extension.iastate.edu/AgDM/livestock/html/b1-65.html Accessed on 9 February 2009.

Michigan Department of Agriculture. 2008. Generally accepted agricultural and management practices for manure management and utilization. *Michigan Commission of Agriculture.*

MWPS. 1993. Livestock Waste Facilities Handbook. 2nd ed. Ames, Iowa: Midwest Plan Service.

Midwest Plan Services. "Manure Characteristics." *Manure Management Systems Series.* MWPS-18, Sect 1, 2nd Edition. 2001.

Rotz, C.A. M.C. Corson, D.C. Chianese, and C.U. Coiner. 2008. "The Integrated Farm System Model—Reference Manual 3.0." Pasture Systems and Watershed Management Research Unit. Agricultural Research Service. United States Department of Agriculture. Available at: http://ars.usda.gov/SP2UserFiles/Place/19020000/ifsmreference.pdf Accessed on 9 February 2009.

Rotz, C.A., and T.M. Harrigan. 2005. Predicting Suitable Days For Field Machinery Operations in a Whole Farm Simulation. *Applied Eng. Agric.* 21(4): 563-517.

Vitosh, M.L, J.W. Johnson, and D.B. Mengel. 1995 "Tri-State Fertilizer Recommendations for Corn, Soybeans, Wheat, and Alfalfa." The Ohio State University Extension Bulletin: E-2567.

Warncke, D., J. Dahl, L. Jacobs, and C Laboski. *Nutrient Recommendations for Field Crops in Michigan.* MSU Extension Bulletin E-2904, May 2004.

Wittenberg E., and C.A. Wolf. "2004 Michigan Dairy Farm Business Analysis Summary." Staff Paper 2005-10, Sept. 2005.

CHAPTER 4: IMPLICATINS OF AN AIR EMISSIONS TAX ON LIVESTOCK PRODUCER'S INVESTMENT IN ABATEMENT TECHNOLOGY

4.1 Introduction

Environmental regulation of livestock production continues to become more stringent as knowledge increases about production processes generating emissions and appropriate abatement technology required to control these emissions. In order to remain profitable agricultural producers must be cognizant of these changes and their implications on future emission-reducing technology investment decisions.

Increasing attention on regulating greenhouse gas emissions under the Clean Air Act from non-point pollution sources, such as the agricultural sector, has been evident with the introduction of the Environmental Protection Agency's 2005 Air Compliance Agreement (Environmental Protection Agency, 2009) and potential climate legislation. Livestock producers had an option to sign this agreement and pay a fee to EPA for unknown past emissions that would be used to collect data on animal air emissions for various livestock enterprises and management practices. In return for signing the agreement, producers were not held liable for any emissions in the interim period prior to implementation of air emission policies—perhaps in 2011 or 2012 and agreed to abide by the decision. By declining to sign the agreement, those producers were left open to penalties for emissions during the interim period. This agreement foreshadows the reality that policy instruments in the form of carbon-equivalent air emission standards, taxes, or some combination thereof will be part of agricultural producer management decisions in the near future.

Air emissions from livestock production are a function of livestock species, housing, and manure storage and application methods. Estimates of livestock air emissions vary greatly as a function of these factors and the study area (Koelsch and Stowell, 2009, USDA/ARS, 2008; Gay et al., 2003). For example, daily ammonia (NH_3) air emissions estimates for a dairy cow based on a Texas study vary from 0.025-0.25 lbs/day (USDA/ARS, 2008) whereas air emissions range from 0.10-1.02 lbs/day based on a Nebraska emissions estimate (Koelsch and Stowell, 2009). If a dairy farm is located in an area where a study has not been completed (as is the case for many livestock operations) the large variation in estimated air emissions makes it difficult for livestock producers to know if they are exceeding air emission limits.

Livestock producers can adopt abatement technologies to reduce animal emission levels. These exist for housing, manure storage, and manure application practices. Housing abatement technologies include bio-filtration system and urine-feces separation. Building long-term manure storage facilities with manure storage covers are examples of storage abatement technologies. Many times these abatement technologies involve irreversible investments with sunk costs. For example, installing a long-term manure storage facility involves a large capital investment which is specific to the livestock enterprise and farm size. There is limited ability for the farmer to sell the manure storage facility if they decide to exit the industry or later learn that a different abatement technology would better suit the needs of their farm based on changing emission regulations. Therefore livestock producers must evaluate the trade-offs of various abatement technologies while considering the uncertainty surrounding future air emission regulations.

A farmer's incentive to invest in emission-reducing technology is influenced by the environmental regulation chosen by the governmental agency. The policy instrument can be market based (emission taxes or tradable pollution permits) or take on the form of a command-and-control policy (performance and technology standards). It has been argued that taxes encourage firms to invest in more efficient pollution abatement technologies than other market-based pollution control methods (Caswell, Lichtenberg, and Zilberman, 1990; Farzin and Kort, 2000; Millman and Prince, 1989; Tarui and Polasky, 2005). Indeed much of the discussion regarding the Air Compliance Agreement has focused on emission taxes as the likely policy instrument. The American Farm Bureau Foundation estimated yearly emission taxes for livestock operations at $175/dairy cow, $87.50/beef cow, and $21.87/hog. These emissions taxes were projected to apply to any agricultural operation with more than 25 dairy cows, 50 beef cattle, 200 hogs, or 500 acres of corn (Dairy Herd Management, 2009). If emission taxes are chosen as the environmental policy control instrument, these estimated animal levels indicate that almost all farms would face some form of an emission tax. To decrease future potential emission tax burdens, livestock producers can adopt abatement technologies. However, the level at which they adopt these technologies is dependent on the "estimated" tax rate.

Past literature has evaluated the behavior of a firm subject to environmental regulation. Xepapadeas (1992) used an infinite planning horizon dynamic game framework to develop incentive schemes for investment which accounted for the dynamics of non-point source pollution problems. Xepadadeas concluded that an increase in an emission tax always resulted in a larger stock of abatement capital for the firm compared to an emission standard. A static incentive scheme was solved and compared to the dynamic solution which suggested that static incentives schemes were suboptimal in the long run.

Kort (1996) extended the theoretical framework of Xepapadeas (1992) assuming that abatement technology would be required to reduce pollution. He evaluated the effect of a pollution tax and marketable permits on firm investment in abatement technology. Productive capital stock was the single input used in the production process, which generated a by-product, emissions. Emissions were generated as function of two forms of capital stock, productive and non-productive, where non-productive capital stock cleaned pollution generated by productive capital stock. Defining the emissions function is the manner extends the work of Xepapadeas to account for the fact that it is more difficult to reduce emissions with abatement technology when emissions are already at a low level. Using an optimal control theory model Kort determined that an increase in a pollution tax does not always result in a decrease of productive capital stock and increase in non-productive capital stock as was found previously by Xepapadeas. Kort also found that in the long-run firm investment behavior was equivalent whether a pollution tax or marketable permit was imposed.

Hartl and Kort (1996) evaluated switching to cleaner inputs in the production process of a firm when an emissions tax was imposed. Emissions were assumed to be generated through a production process defined by a single input, capital stock. Hartl and Kort included an investment grant in the decision that was found to induce investment at a relatively earlier date.

Farzin and Kort (2000) extend Hartl and Kort's model to consider two forms of uncertainty for the optimal investment policy of a firm facing environmental regulation:

(1) an increase of unknown size in the future pollution tax rate and (2) an unknown timing of the tax increase. Secondly, Farzin and Kort assumed that emissions were a function of the production process as defined by a single variable input rather than capital stock as specified in Hartl and Kort. This assumption allows the firm to decrease emissions by decreasing the variable input, rather than the capital stock level. Farzin and Kort determined that abatement investment rates were lower than the certainty case when uncertainty existed about the magnitude of the future tax increase. Uncertainty surrounding emission tax increase timing resulted in increased under-investment in abatement capital.

Investment in emission reducing technologies is a dynamic and potentially irreversible investment for many agricultural producers. Livestock producers are aware that an environmental policy instrument is scheduled to be imposed for air emissions December 31, 2011. However, uncertainty exists surrounding the stringency of new environmental regulations regarding air emissions for livestock operations. Producers must evaluate tradeoffs between investing in emission-reducing technology today versus waiting to invest at a later date when additional information regarding new emission reducing technologies could become available.

A study that combines the theoretical framework developed by Kort (1996) which specified a emissions production function dependent on productive and non-productive capital stock and uncertainty surrounding the size of an emissions tax developed by Farzin and Kort (2000) is absent in current literature. Combining these two topics allows for an analysis of the current situation faced by livestock producers where animals are productive capital stock and abatement technology is non-productive capital stock.

Secondly, uncertainty is included with an uncertain emission tax increase imposed on December 31, 2011. Determining how a livestock producer's investment path changes based on current estimates of an emission tax rate allows us to better understand how the dairy industry will respond to different levels of emission taxes.

This analysis adapts the model of Farzin and Kort (2000) to evaluate the effect of an emission tax policy on farm investment in emission-reducing technology. This analysis differs from Farzin and Kort's in three ways. First, the production process is defined as a function of productive capital rather than a variable input, since animals are a form of capital on livestock operations. Second, in addition to a productive capital stock, non-productive capital stock is introduced in the model to reduce emissions. Therefore a functional form for the emissions function is defined to address the interaction between productive and non-productive capital stock as outlined by Kort (1996), rather than a pollution function proportional to output level used by Farzin and Kort (2000). Finally, an empirical analysis is implemented at the aggregate level which has been absent in previous analysis. Functional forms for milk production and emissions functions, and numeric values for price and tax parameters are defined to provide a tractable analysis which can be used in a policy context. The objective of this analysis is to determine the optimal investment path for (1) a certain emission tax at time $t=0$ and (2) an uncertain emission tax increase at time T which considers the potential uncertainty regarding environmental regulation faced by agricultural producers.

The paper proceeds as follows. In section 4.2 an analytical model of an emission tax that is known with certainty and does not change over time is presented for the dairy industry which is followed by an empirical analysis of the basic tax model for a known low and high tax rate in Section 4.3. Section 4.4 presents an analytical analysis of an unknown tax rate at a known time T with the empirical analysis in Section 4.5. Discussion, policy implications, and conclusions are presented in Section 4.6.

4.2 Basic Emission Tax Model

The basic model adapted from Farzin and Kort (2000) is an emission tax that is known with certainty and does not change over time. The basic model is applied to the dairy industry herd population at an aggregate level but could be directly applied to other livestock enterprises. The results of this basic model are used as a benchmark to analyze uncertain tax policy in later sections.

Consider a risk-neutral farmer which has the opportunity to invest in two types of capital, productive and non-productive. The productive capital is an input (dairy cows, (Ω)) used to produce a homogenous output (milk) according to a simple production process

(1) $m=m(\Omega)$,

where $m(0)=0$, $m'(\Omega)>0$, and $m''(\Omega)\leq 0$. Jointly with milk production, emissions are generated as a function of the input level of productive capital stock, cows (Ω). The second type of capital (K) used by the farm is non-productive, but reduces emissions generated by the productive capital stock, Ω. Examples of non-productive capital include animal housing, manure storage, and manure application methods used to minimize emissions (Gay et al., 2003; Koelsch and Stowell, 2009). The animal emissions function is given by

(2) $A=A(\Omega,K)$,

where A is total emissions generated by productive and non-productive capital. The emissions function must satisfy the following conditions (Kort, 1996):

$$\text{(2a)} \quad A(\Omega, K) > 0 \textit{ for all } \Omega > 0 \textit{ and } K \geq 0,$$

$$\text{(2b)} \quad A_{\Omega}(\Omega, K) > 0 \text{ and } A_{\Omega\Omega}(\Omega, K) > 0,$$

$$\text{(2c)} \quad A_{K}(\Omega, K) < 0 \text{ for all } \Omega > 0 \text{ and } A_{KK}(\Omega, K) > 0 \text{ for all } \Omega > 0$$

$$\text{(2d)} \quad A_{\Omega K}(\Omega, K) = A_{K\Omega}(\Omega, K) < 0.$$

Condition (2a) implies that emissions are positive as long as cows are on the farm. Condition (2b) shows that emissions increase in a convex way with an increasing number of cows for a given level of emission-reducing capital. Diminishing returns for emission-reducing technologies is shown with condition (2c) which states that emission output is smaller for larger amounts of emission-reducing technologies for a given level of cows (Ω). Condition (2d) implies that an increase in emissions due to one additional cow is smaller for larger stocks of emission-reducing capital. Therefore, emission-reducing technologies are more effective for reducing emissions than reducing the number of cows on the farm. The emissions function is not separable in Ω and K which implies that increased investments in emission-reducing capital stock is required to reduce emissions with some fixed level of productive capital, Ω.

Following Chavas and Klemme (1987) aggregate dairy herd population dynamics are a function of the current level of cows in the female population, a survival rate, and a net birth rate. The survival rate is defined as the proportion of animals still in the dairy population after one time period. The net birth rate is the difference between the birth rate and a constant natural death rate for offspring. The dynamics of the adult female population can be written as $\dot{\Omega} = \alpha\Omega S$, where α is the net birth rate and S is the survival rate of cows. We assume that the birth rate and survival rate are independent of the size of the dairy cow population. Since cows produce emissions as a by-product of the milk production process, decreasing the number of cows through slaughter (which changes the survival rate of the cows) decreases the amount of emissions generated.

Emission abatement capital stock can be increased by making an investment, *I*, in emission-reducing technology. The total investment cost, *C(I)*, is assumed to be a convex increasing function of the investment level such that,

$$(3) \qquad C(0) = 0,$$

where $C'(I)>0$ and $C''(I)>0$. It is assumed that investment in emission abatement technology is irreversible such that $I \geq 0$. Without investment, *I*, emission abatement capital stock is assumed to depreciate at a constant proportional rate of δ.

An emission tax, $\tau > 0$, is defined as the pollution tax per unit of emissions. The total farm emissions tax payment at any point in time is $\tau A(cows, K)$.

The management decision for the farms is to choose the survival rate, *S*, (or consequently the cull rate (*1-S*)) and emission-reducing technology investment, *I*, to maximize the present value of its cash flows over an infinite planning period,

$$(4) \qquad \max_{S,I} \int_0^{\infty} \left[p_m m(\Omega) + p_s \Omega(1-d)(1-S) - w\Omega - C(I) - \tau A(\Omega, K)\right] e^{-rt} dt,$$

$$\text{s.t.} \quad \dot{\Omega} = \alpha\Omega S$$

$$\dot{K} = I - \delta K,$$

$$I \geq 0.$$

where Ω is the productive capital stock (cows), $m(\Omega)$ is the milk production function, p_m is the market milk price, p_S is the market slaughter price, d is the death loss among cows, S is the survival rate, w is the input price of milk production (ie. feed for cows), K is the non-productive capital stock (ie. manure storage), I is the emission-reducing technology investment, $A(\Omega, K)$ is the emissions production function, α is the net birth rate, τ is the per anima emissions tax, δ is the depreciation rate for non-productive capital stock, K and r is the constant discount rate.

Equation (5) simply states that the returns at time t are equal to the revenue from milk production plus the revenue from an animal leaving the population (ie. slaughter value) less the input costs for milk production, investment costs for emission-reducing technology, and the emission tax liability faced by the industry. The current value Hamiltonian for the optimal control problem is defined as,

(5)

$$H = p_m m(\Omega) + p_S \Omega(1-d)(1-S) - w\Omega - C(I) - \tau A(\Omega, K) - \lambda(\alpha\Omega S) - \eta(I - \delta K)$$

where λ is the shadow price of the productive capital, cows, and η is the shadow price of non-productive capital, emission reducing technology. The necessary conditions for the optimal policy are,

(6) $$\lambda = \frac{p_s(1-d)}{\alpha},$$

(7) $$\eta = C'(I),$$

(8) $$\dot{\lambda} = (r - \alpha)\lambda - p_m m'(\Omega) - p_S(1-d)(1-S) + w + \tau A_\Omega(\Omega, K)$$

(9) $$\dot{\eta} = (r + \delta)\eta + \tau A_K(\Omega, K).$$

Equation (6) shows the marginal impact of cow sales on the Hamiltonian where the shadow price of cows must equal the slaughter price adjusted by the net birth rate and natural death loss along the optimal slaughter path. Equation (7) shows that the shadow price of the emission-reducing technology must equal its marginal cost along the optimal investment path. Equation (8) is the adjoint condition which states that an additional cow slaughtered is equal to the net revenue from that cow. Equation (9) is the adjoint condition which states that an additional unit of investment is equal to the savings on the emissions tax payment. The adjoint equations must hold at each point in time and can be expressed as "golden rule" equations (typically found in resource management literature) by taking the time derivative of the shadow price equation and setting it equal to the adjoint condition for λ and η. Taking the time derivative of equation (6) and setting it equal to equation (8) and solving for, *r*, results in,

$$(10) \quad r = \frac{p_m m'(\Omega))}{\lambda} - \frac{w}{\lambda} - \frac{\tau A_\Omega(\Omega, K)}{\lambda} + \alpha .$$

Equation (10) equates the return from holding dairy cows (not slaughtering) to its opportunity cost, *r*. The first and second RHS terms are the marginal revenue and cost from keeping the dairy cow in the milking population, respectively. The third term is the tax cost of investing in a larger dairy population at the margin. The fourth term is the marginal impact of cows on reproduction.

Taking the time derivative of equation (7) and setting it equal to equation (9) and solving for *r* results in,

$$(11) \quad r = \left[\frac{C''(I)\dot{I}}{C'(I)} - \delta \right] - \frac{\tau A_K(\Omega, K)}{C'(I)} .$$

Equation (11) equates the return from not investing in emission-reducing technology to its opportunity cost, *r*. The first RHS term in the bracket is the capital gains to emission reducing technology less depreciation.[7] The second RHS term is the marginal impact of taxes on investing in new emission-reducing technology.

From equation (6) we know that $\lambda = \frac{p_S(1-d)}{\alpha}$, which results in a singular solution for the survival rate control variable since there are no control variables in equation (10). Therefore, we can solve for the number of cows in the herd as a function of capital (*K)*, rather than *S*. The number of cows in the dairy herd changes as the emission-reducing capital stock changes. We can solve for the $\dot{I} = 0$ and $\dot{K} = 0$ isoclines to analyze the phase diagram for the optimal investment path in the (*K,I*)-plane rather than the (*K,S)*-plane. The $\dot{K} = 0$ isocline is a positively sloped straight line where $I = \delta K$. The isocline for $\dot{I} = 0$ is defined by solving for $\dot{I}$ in equation (11) such that,

$$(12) \quad \dot{I} = \frac{(r+\delta)C'(I) + \tau A_K(\Omega, K)}{C''(I)}.$$

From equation (12), a unique saddle point exists where $\dot{I} = \dot{K} = \dot{\eta} = 0$ and $I = \delta K^*$ such that,

$$(13) \quad -\tau A_K(\Omega^*, K^*) = (r+\delta)C'(\delta K^*).$$

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[7] The first RHS term in equation (11) can also be represented as $\frac{\dot{\eta}}{\eta}$ where $\dot{\eta} = C''(I)\dot{I}$ and $\eta = C'(I)$.

4.3 Numerical Example: Basic Emissions Tax Model

A numerical application of the basic emissions tax model was implemented to analyze the numerical phase plane diagram in the (K,I)-plane rather than theoretical diagrams completed in previous analysis (Farzin and Kort, 2000). Data used to parameterize the model are provided in Table 4a. Prices parameters used in the model were based on dairy industry average values. Slaughter price was valued at \$650/cwt based on a five year average for dairy cow slaughter prices from USDA-NASS (2001-2006). Feed cost was assumed to be \$4.68/cow/day for purchased, homegrown, and grazing feed which resulted in a yearly cost of \$1,709/cow (ARMS-ERS, 2005).

The American Farm Bureau estimated a potential emissions tax for dairy of \$175/cow. The emissions tax rate in the model is specified based on units of emissions. The per animal emissions tax rate is converted to pounds of ammonia (NH_3) emissions assuming that a dairy cow produces 0.25 pounds of ammonia emissions on a daily basis or 91.25 pounds annually (USDA/ARS, 2009; Gay et al., 2003).[8] The emission tax rate was calculated as \$1.92/lb NH_3 emissions.

The depreciation rate for capital, δ, was assumed to be 0.05 which assumes a 10 year useful life of the emission-reducing technology investment. A discount rate of 0.09 was used (Wolf et al., 2002).

A constant returns to scale milk production function was implemented to estimate milk production such that, $m(\Omega) = 210\Omega$. It was assumed that the average yearly milk

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[8] 0.25 pounds of ammonia emissions is the most common value used to estimate emissions and was used to adjust a per cow tax to per pound ammonia (NH3) emissions.

yield was 21,000 pounds per cow. Annual yield was converted to hundredweight (cwt) basis to be in equivalent unit terms for milk price.

The milk price *pm* is endogenous in the model since the demand for milk is downward sloping. An inverse demand function for milk was used to determine the price of milk within the model as a function of the number of cows. The inverse demand function was defined assuming aggregate milk production was 190 billion pounds of milk with average milk production per cow of 21,000 pounds. A CES production function was assumed for quantity demanded with the simplifying assumption that cows are the only input in the milk production process. The inverse demand function was,

$p_m = 5978 - \frac{Q_D}{304{,}237}$, where the quantity demanded for milk, $Q_D = 2100[\Omega^{-0.9}]^{-1/0.9}$.

Dairy herd population dynamics is a function of the natural death rate, survival rate, and net birth rate. The natural death rate, *d*, for dairy cows was assumed to be 4.91% (McDonald et al., 2007). The net birth rate was valued at 1.8 (McDonald et al., 2007).

The functional form for the emissions production was specified using conditions (2a)-(2d) which resulted in $A(\Omega, K) = \Omega^{0.5}K^{-0.5}$. The negative coefficient on the non-productive capital, *K*, means that as the amount of emission-reducing capital stock increases through emission-reducing technology investment, animal emissions decrease.

Total investment cost was assumed to be a convex increasing function of the investment level in the emission-reducing technology. This resulted in the following function form of, $C(I) = \frac{1}{2} I^2$ for investment cost.

Table 4a. Parameter description, values, and sources

Parameters	Description	Value	Source
p_s	Slaughter price	\$650/cow	USDA-NASS (2001-2006)
w	Feed cost	\$1,709/yr/cow (\$4.68/day/cow)	ARMS-ERS (2005)
τ	Tax rate	\$1.92/emission unit (\$175/cow)	American Farm Bureau (2009)
δ	Depreciation rate for non-productive capital	0.05	Assumption
r	Discount rate	0.09	Wolf et al. 2002
α	Net birth rate	1.8	Assumption
d	Death rate	0.491	McDonald et al. 2007
$m(\Omega)$	Milk production function	210Ω	Assumption
$A(\Omega, K)$	Air emissions production function	$365\Omega^{0.5}K^{-0.5}$	Assumption
$C(I)$	Investment cost function	$0.5I^2$	Kort and Hartl (1996)

Using the assumptions in Table 4a, the numerical equivalents for equation (6)-(9) for the optimal control theory problem with a certain tax rate $\tau = 1.92$ /lb ammonia emissions are the following,

(14) $\lambda = 343,$

(16) $\eta = I,$

(17) $$\dot{\lambda} = 0.09\lambda + 1091 + 0.15\Omega - 210\left[5978 - \frac{210\Omega}{304{,}237}\right] + \frac{350.4}{\Omega^{1/2}K^{1/2}}$$

(18) $$\dot{\eta} = 0.19\eta - \frac{350.4\Omega^{1/2}}{K^{3/2}}.$$

Taking the time derivative of (14) and setting it equal to (17) we can solve for Ω in terms of emission-reducing capital since we have a singular solution for the survival rate control variable. Substituting Ω in terms of K into (17) allows us to plot the isoclines for $\dot{I} = 0$ and $\dot{K} = 0$ for a tax rate $\tau = \$1.92/\text{lb}$ ammonia as a numerical result for a singular solution with respect to the survival rate control variable (Figure 4a). The thin line in Figure 4a is the saddle path leading to the stable steady state equilibrium where I=45and K=900. Along the saddle path investment falls as emission-reducing capital stock increases. This is a result of the functional form for the emissions production function including both cows (productive) and emission-reducing (non-productive) capital stock. The phase-plane diagram shows that with low levels of aggregate of emission-reducing capital stock (i.e., K=300) and investment level of I=100 is needed for the dairy industry to reach the saddle path for investment and move towards the steady state equilibrium level of investment in emission-reducing technology and non-productive capital stock.

Along the optimal investment path (saddle path) the shadow price must always equal the marginal cost such that,

(20) $$\int_t^{\infty} -\tau A_K(\Omega, K) e^{-(r+\delta)(s-t)} ds = C'(I(t)) = \eta$$

where the LHS expression of the equation is the reduction in emission tax payments resulting from an additional unit of emission-reducing technology investment at time t.

When aggregate emission-reducing capital stock is relatively low (i.e., *K=300*) the optimal investment rate is high and decreases over time as it reaches the steady state at equilibrium at point A. High levels of emission-reducing capital stock (*K*>900) requires lower investment levels to reach the investment saddle path and the steady state equilibrium for investment in emission-reducing technology and non-productive capital stock as compared to low initial capital stock levels.

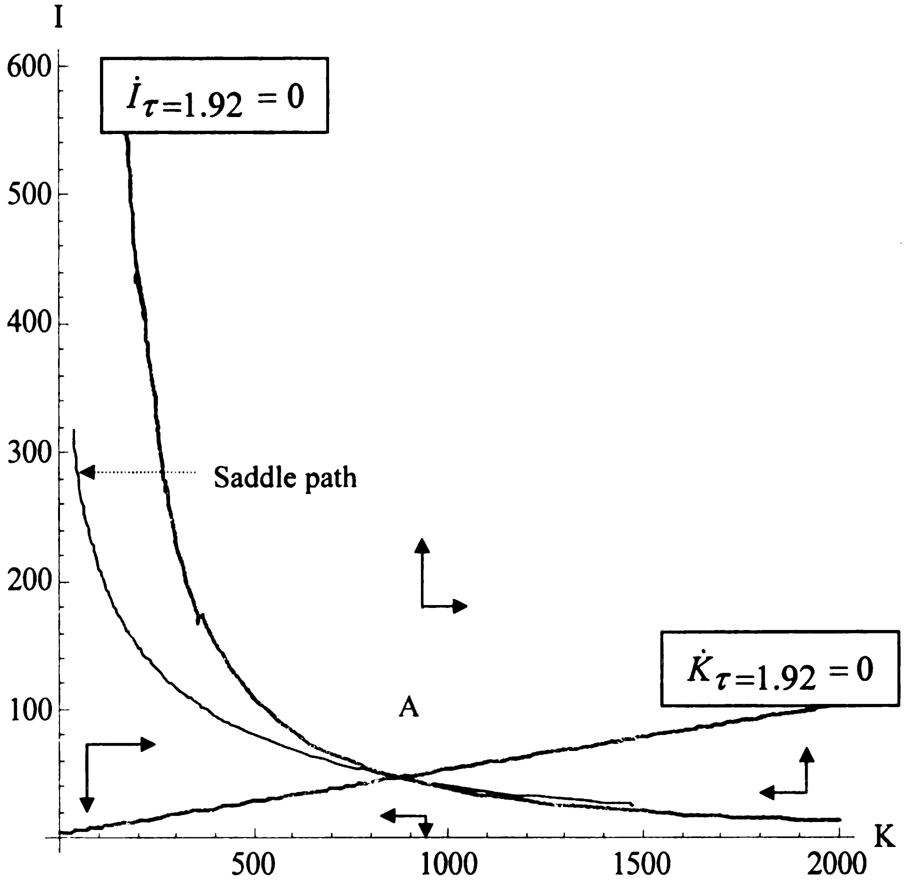

Figure 4a. Optimal investment path for τ = \$1.92 /lb ammonia emissions

The tax rate level influences investment decisions made by farmers. In the model we assumed τ = \$1.92 per lb of ammonia emissions (\$175/cow) which is a high tax rate.

For example an individual dairy farm with 100 cows would incur \$17,500 in emission taxes. If the milk price is \$14/cwt and a dairy cows produces 70 pounds of milk per day per cow, milk production revenue for approximately 18 days would be needed to pay the emission tax. A second tax rate was included in the analysis to compare how investment decisions change with a lower tax rate. We assumed the lower tax rate was, $\tau_L = \$0.48$ per lb ammonia emission, which was 75% lower than the tax rate reported by the American Farm Bureau (2009).

Figure 4b presents the phase-plane diagram for $\tau_H = \$1.92$ and $\tau_L = \$0.48$ /lb ammonia emissions. The $\dot{K} = 0$ isocline did not change with a new tax rate. $\dot{I}_{\tau l = 0.48} = 0$ shifted downward with the lower tax rate (red line in Figure 4b). The steady state equilibrium for $\tau_L = \$0.48$ is represented by point B with I=25 and K=516. Increasing the tax rate by 75% (τ_L to τ_H) increased the optimal investment rate by 80% and emission reducing capital stock by 74%. With the tax increase from τ_L to τ_H the productive capital stock, *cows*, in the dairy industry remained constant while the non-productive capital stock, *K*, increased. It was more efficient for the industry to add emission-reducing technologies on farms to decrease emission tax payments rather than decreasing the aggregate herd population. Implicitly, the tax payment faced by an individual farm is $\tau 365 \Omega^{1/2} K^{-1/2}$. Taking the derivative of the tax payment with respect to emission-reducing capital, *K*, results in $-183\tau\Omega^{1/2} K^{-3/2} < 0$ which shows that the emission tax payment decreases as emission-reducing capital stock increases.

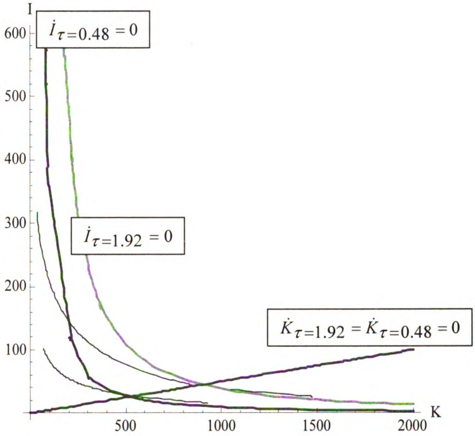

Figure 4b. Optimal investment path for $\tau_H = \$1.92$ and $\tau_L = \$0.48$ /lb ammonia emission

Figures 4a and 4b demonstrate that as the emissions tax rate increases investment levels must also increase in order to decrease or avoid the potential tax liability. The optimization problem presented in equation (5) was solved for a series of emission tax rates to determine how the amount of emission-reducing capital stock changed per cow as the tax rate increased. Due to the specification of this model, the number of dairy cows remained constant at its current industry level. As shown previously, it was more efficient for the dairy industry to increase the emission-reducing capital stock rather than decrease the aggregate herd size. Figure 4c demonstrates that as the tax rate increases, the equilibrium level of capital stock per cow must increase. Therefore the investment level per cows must also increase to adjust for the increased levels of emission-reducing capital stock.

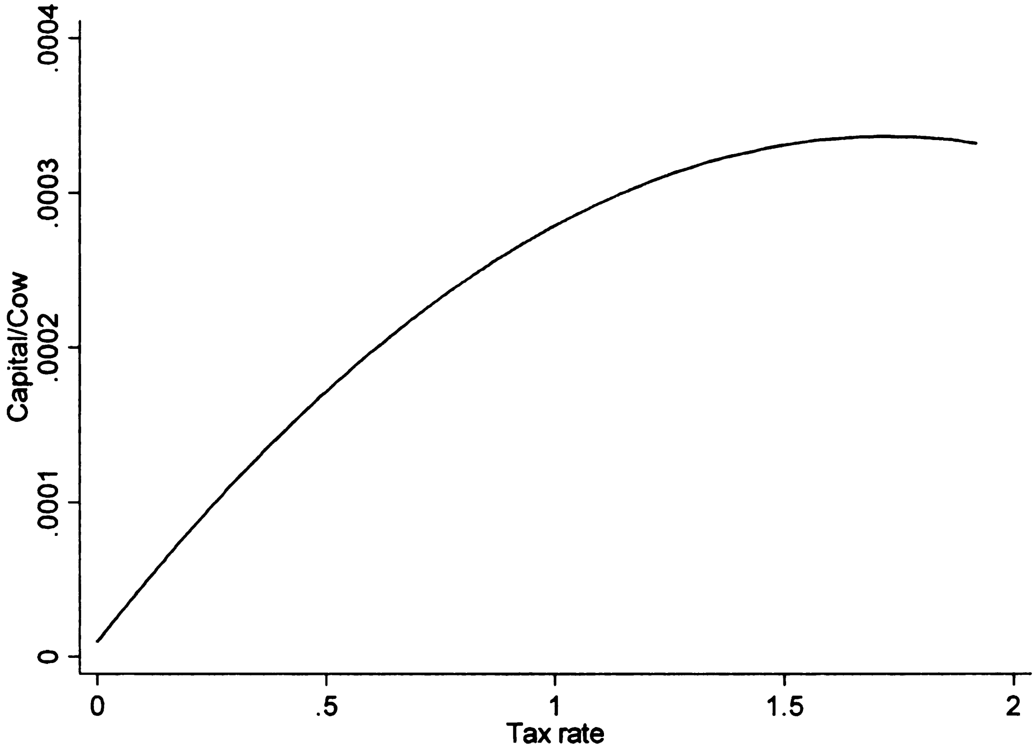

Figure 4c. Emission-reducing capital stock per cow as tax rate increases

4.4 An Uncertain Emissions Tax Increase at a known Future Date

We now consider the case where an emissions tax will be imposed at a known future date, *T*, but the magnitude of the emission tax is uncertain. For this problem the dairy industry (all dairy farmers) consider potential tax rates that may be imposed at time *T*, to adjust investment rates in emission-reducing technology from time $t=0$ to $t=T$. At time *T*, the actual tax rate is revealed and a jump in the investment rate may occur to adjust to the desired saddle path.

Before we solve the case with an uncertain tax increase, it is useful to analyze the case where the tax increase is known with certainty. Suppose a low tax rate, τ_L, is imposed and at time *T*, the tax rate increases to τ_H which results in the following maximization problem,

$$\text{(20)} \quad \max_{S,I} \int_0^T \left[p_m m(\Omega) + p_s\Omega(1-d)(1-S) - w\Omega - C(I) - \tau_L A(\Omega,K)\right]e^{-rt}dt$$

$$+ \int_T^\infty \left[p_m m(\Omega) + p_s\Omega(1-d)(1-S) - w\Omega - C(I) - \tau_H A(\Omega,K)\right]e^{-rt}dt$$

$$\text{s.t} \quad \dot{\Omega} = \alpha\Omega S, \quad \Omega_0(0)$$

$$\dot{K} = I - \delta K, \quad K_0(0)$$

Using the example presented in the previous section and Figure 4b, the investment rate for the aggregate dairy industry must adjust to account for the higher tax rate imposed at time *T*. With an increase to τ_H, the farmer's investment rate will deviate away from the saddle path for $\dot{I}_{\tau_L} = 0$ and move towards the saddle path for $\dot{I}_{\tau_H} = 0$ as shown by the dashed line in Figure 4d. The new investment rate in emission-reducing technology changes such that at time *T* when τ_H is imposed, the farmers are on the saddle path for τ_H and moving towards (or at) the steady state equilibrium (point A) for τ_H.

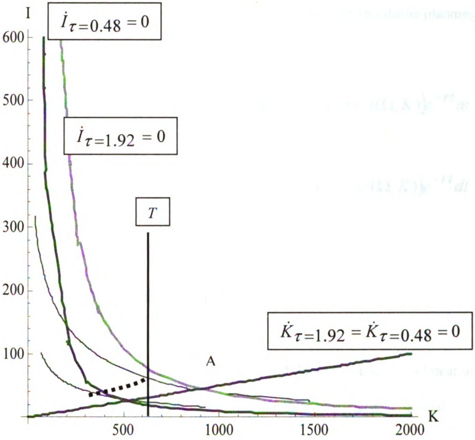

Figure 4d. Optimal investment path for a tax increase from $\tau_L = \$0.48$ to $\tau_H = \$1.92$ at time *T*.

With an uncertain emission tax increase, there is uncertainty regarding how to adjust the investment rate in emission-reducing technology by time *T*. The new problem considering this uncertainty can be set-up as a two-stage optimal control problem where in the second stage the expected present value of cash flows is maximized since the tax increase is unknown (Dosi and Moretto, 1990). In the first stage the present value of cash flows is maximized with the constraint that the cash flows at time *T* must be equal to the present value cash flows calculated in stage two of the optimal control problem. This leads to the farmers choosing the survival rate, S, and emission-reducing technology investment, I, to maximize the present value of its cash flows over an infinite planning period such that,

$$\text{(21)} \quad \max_{S,I} \int_0^T [p_m m(\Omega) + p_s \Omega(1-d)(1-S) - w\Omega - C(I) - \tau_L A(\Omega, K)] e^{-rt} dt$$

$$+ E \int_T^\infty [p_m m(\Omega) + p_s \Omega(1-d)(1-S) - w\Omega - C(I) - \tau A(\Omega, K)] e^{-rt} dt$$

$$\text{s.t} \quad \dot{\Omega} = \alpha \Omega S, \quad \Omega_0(0)$$

$$\dot{K} = I - \delta K, \quad K_0(0)$$

We assume all dairy farmers are risk neutral and the profit function is linear in taxes such that $\pi E(\tau) = E(\pi(\tau))$ which implies that the comparison of optimal investment paths with full certainty versus uncertainty depends on the tax rate at time T and expected tax rate after time T. To solve the two stage optimal control problem we first solve the second term of equation (21),

(22)

$$\max_{S,I} e^{-rt} E \int_T^\infty [p_m m(\Omega) + p_s \Omega(1-d)(1-S) - w\Omega - C(I) - \tau A(\Omega, K)] e^{-r(t-T)} dt$$

$$\text{s.t} \quad \dot{\Omega} = \alpha \Omega S, \quad \Omega_0(0)$$

$$\dot{K} = I - \delta K, \quad K_0(0)$$

Following this, the numerical solution to the second stage, $e^{-rt}\pi(K(\tau_T),\Omega(\tau_T),\tau_T)$, is included in the first stage problem,

$$(23)\ \max_{S,I} \int_0^T \left[p_m m(\Omega) + p_s\Omega(1-d)(1-S) - w\Omega - C(I) - \tau_L A(\Omega,K)\right]e^{-rt}dt$$
$$+ e^{-rt}\pi(K(\tau_T),\Omega(\tau_T),\tau_T)$$
$$\text{s.t}\quad \dot{\Omega} = \alpha\Omega S,\ \ \Omega_0(0),\ \ \dot{K} = I - \delta K,\ \ K_0(0)$$

The necessary conditions for the optimal investment policy must include,

$$(24)\qquad \lambda = \frac{p_s(1-d)}{\alpha} = \frac{\partial\pi(K(\tau_T),\Omega(\tau_T),\tau_T)}{\partial\Omega}$$

$$(25)\qquad \eta = C'(I) = \frac{\partial\pi(K(\tau_T),\Omega(\tau_T),\tau_T)}{\partial K}.$$

If conditions (24) and (25) do not hold, the present value cash flows from stage one will not be equal to the present value calculated in stage two.

The numerical solution for the expected profit in the second stage is dependent on the tax rate. The optimal investment path was calculated for each tax rate ($\tau_1,\tau_2,$ and τ_3) for a given level of emission-reducing capital stock. The expected profit is,

$$(26)\qquad E(\pi|K_{0(i)}) = p(\tau_1)\pi(\tau_1) + p(\tau_2)\pi(\tau_2) + p(\tau_3)\pi(\tau_3)$$
$$= e^{-rt}\pi(K(\tau_T),cows(\tau_T),\tau_T).$$

The results of equation (26) are then included in the first stage regression to solve the optimal control theory problem for an uncertain tax increase at time *T*.

4.5 Empirical analysis of uncertain tax

The two-stage optimal control theory model shows that the dairy industry takes into account future tax rate increases to adjust (or not adjust) investment in emission-reducing capital stock even though the tax rate is not imposed until time *T*. There are two cases that can be analyzed with the two-stage optimal control model. The first case is when the dairy industry is faced with a low tax rate from time *t=0* and knows a tax increase will be imposed at time *T*. This two stage problem is equivalent to equation (23).

In the second case, an emission tax is not imposed in the first stage of the problem. Therefore, the adjustment to the optimal investment rate is dependent on the expected tax rate imposed at time *T* and its effect on the profit function for time *T* to infinity. The two-stage optimal control theory problem for case 2 is,

$$(27)\quad \max_{S,I} \int_0^T [p_m m(\Omega) + p_S \Omega(1-d)(1-S) - w\Omega - C(I)]e^{-rt}dt$$

$$+ e^{-rt}\pi(K(\tau_T), \Omega(\tau_T), \tau_T)$$

$$\text{s.t}\quad \dot{\Omega} = \alpha\Omega S,\quad \Omega_0(0),\quad \dot{K} = I - \delta K,\quad K_0(0).$$

It may be hypothesized that without a tax imposed at time *t=0,* there exists little incentive to invest in emission-reducing technology. However, the possibility of future emissions taxes may create incentive to increase investment in emission-reducing technologies up to time *t=T*.

A numerical application of an uncertain tax increase at time *T* was implemented using the data and parameters presented in Table 4a for the case where there is no initial emissions tax in the first stage of the problem. Three tax rates were assumed with equal probability to estimate the expected profit function for stage two at a given level of emission-reducing capital stock. The three tax rates were: $\tau_1 = \$0$ as the minimum tax, $\tau_2 = \$0.96$ as an average tax, and a maximum tax rate of $\tau_3 = \$1.92$. An equal probability was assigned to each tax rate where $P(\tau_1 = \$0)$=0.33, $P(\tau_2 = \$0.96)$=0.33, and $P(\tau_3 = \$1.92)$=0.33. The expected profit function for a given level of emission reducing capital stock was estimated as,

$$E(\pi|K_{0(i)}) = 0.33\pi(\tau_1 = 0|K_{0(i)}) + 0.33\pi(\tau_2 = 0.96|K_{0(i)})$$

$$+ 0.33)\pi(\tau_3 = 1.92|K_{0(i)}),$$

and included in the first stage problem to solve for the optimal investment rate considering an uncertain tax increase at time T.

Case 1: Low tax rate imposed in stage 1

First, the optimal investment path for an uncertain tax increase at time $t=T$ with a low tax rate $\tau_L = \$0.48$ /lb ammonia emissions imposed from time $t=0$ to $t=T$ was solved and presented in Figure 4e. First, if no tax rate increase was imposed, the management decision for investment would continue on the saddle path for $\dot{I}_{\tau_L}$ towards the steady state equilibrium level of investment in emission-reducing technology and capital for the low tax rate. However, we know that an emission tax increase will occur at time $t=T$, so the management decision for the investment rate level in emission-reducing technology must deviate away from the $\dot{I}_{\tau_L}$ and move towards $\dot{I}_{E(\tau)}$. The rate at of this change in the investment path towards $\dot{I}_{E(\tau)}$ is determined by the transversality conditions holding (equation (24) and (25)).

The investment rate for small levels of emission-reducing capital stock does not deviate from the investment path for the low tax rate, $\tau_L = \$0.48$, since at these points the present value cash flows in stage one are equal to stage two. Uncertainty regarding the increase in the tax rate when a low tax rate is imposed causes a U-shaped investment path for small levels of initial emission-reducing capital stock, such that at small levels of initial emission reducing capital stock, the investment path will not deviate from the low tax rate investment path. However, at an emission-reducing capital stock level of K=252, it is optimal to deviate away from the investment path for the low tax rate and move toward the investment for the expected tax rate. By time T, the dairy industry has adjusted to the saddle path for the expected tax rate. If the actual tax rate is equivalent to the expected tax rate at time T, the dairy industry as a whole is already on the optimal investment path and will move towards the steady state equilibrium level of emission-reducing capital stock through increased investment in emission-reducing technology. If the actual tax rate is higher than the expected rate, there will be an immediate jump upward in the investment rate to the investment saddle path for the actual tax rate. A realized tax rate at time $t=T$ which is less than the expected rate results in investment rates less than depreciation ($I < \delta K$) to reach the new steady state equilibrium.

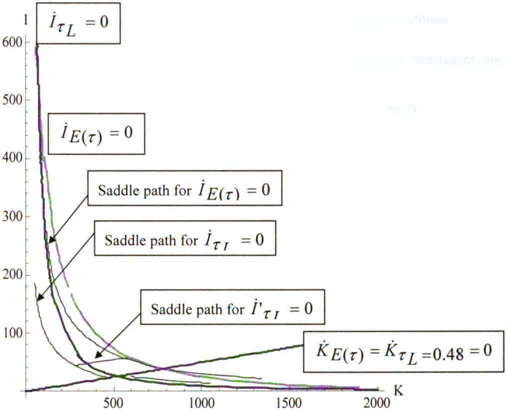

Figure 4e. Optimal investment path for uncertain tax increase at $t=T$ with a low initial tax rate $\tau_L = \$0.48$

Case 2: No tax rate imposed in stage 1

In the second case, the expected future emissions tax at time $t=T$ is the first time a tax has been imposed. Investment rates have not been adjusted previously as was the case when a tax rate was already imposed before the announcement of a tax increase. With the expected future tax, the investment rate in emission-reducing capital stock increases up to time $t=T$ (Figure 4f) for all levels of initial emission-reducing capital stock up the equilibrium for the expected tax rate. To reach the saddle paths for $\dot{I}_{E(\tau)} = 0$ high investment rates must be incurred for low levels of emission-reducing capital without knowing if an actual tax rate will be imposed since there is a positive probability that the tax rate could be zero at time $t=T$. Without prior investment adjustments, $\dot{I}_{E(\tau)} = 0$ all farmers in the industry will need to increase investment rates based on the deviation saddle path, $\dot{I}'_{\tau=0} = 0$ rather than moving directly to $\dot{I}_{E(\tau)} = 0$.

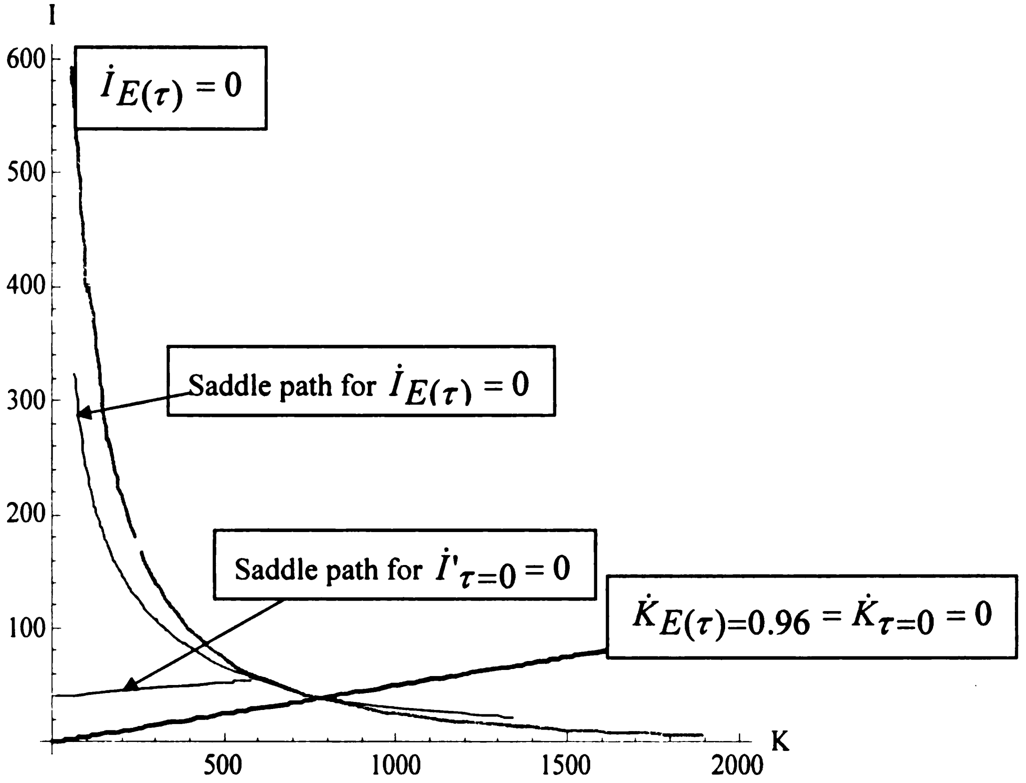

Figure 4f. Optimal investment path for an uncertain tax increase at time $t=T$ with $\tau = 0$ for $t=0$ to $t=T$.

Comparing the change in investment rates for the two cases shows that when the uncertain tax increase is the first time a tax is imposed, adjustment in investment rates occurs for all levels of emission-reducing capital. When an initial low tax rate was imposed in stage one, aggregate emission-reducing capital levels greater than *K=252* adjusted the investment paths towards the expected tax rate. The difference in area between the saddle paths for the optimal investment rate between $\dot{I}'_{\tau_L} = 0$ and $\dot{I}_{E(\tau)} = 0$ were smaller for lower levels of emission-reducing capital compared to the saddle path for $\dot{I}'_{\tau=0} = 0$ and $\dot{I}_{E(\tau)} = 0$. Since the tax increase, of uncertain scale, in time *t=T* is the first introduction of an emissions tax, there are an increased number of possible outcomes for investment rates and greater uncertainty surrounding it compared to the case where there is a positive initial tax rate in the first stage, in which fewer possible outcomes exist.

4.6 Conclusions

The incentive to invest in emission-reducing technology is influenced by the size and type of environmental policy instrument imposed. In this paper, we extended Farzin and Kort's (2000) theoretical model to include a functional form for animal air emissions as a function of productive (cows) and non-productive (emission-reducing capital stock) capital stock. Further, numerical solutions for an introduction of a certain tax rate at time *t=0* and an uncertain tax increase at time *t=T* were estimated for an aggregate dairy population model.

A certain tax rate imposed at time *t=0* resulted in immediate increased investment in emission-reducing technology. An uncertain tax increase imposed at time *t=T* for an initial low tax, $\tau_L = \$0.48$ lb/ ammonia emissions, demonstrated farmers adjusted their investment rates in emission reducing technologies towards the optimal investment level in anticipation of an expected tax increase imposed at time $t=T$. When farmers did not face an initial tax rate at time $t=0$ the amount of investment necessary to achieve the optimal path was increased compared to those farmers who had faced a positive initial tax rate. In other words, because farmers who had not faced any tax rate prior to time $t=T$ had not responded to potential tax increases, greater levels of investment were necessary approaching time $t=T$ relative to those facing positive initial tax rates. Finally, as the tax rate increased, the amount of emission-reducing capital stock per cow increased to decrease the amount of tax liability faced by the industry.

The numerical solution for the optimal investment policy allows policy makers to evaluate how investment rates changed as the tax rate and uncertainty surrounding it changed. This numerical model can be further extended to consider such items as emission standards and tradable permits rather than emission taxes as well as the inclusion of investment grants through cost-share programs to decrease investment costs associated with emission-reducing technologies.

REFERENCES

Caswell, M., E. Lichtenberg, and D. Zilberman. "The effects of pricing policies on water conservation and drainage." *American Journal of Agricultural Economics.* 72(1990):883-890.

Dairy Herd Management. "Headed Down a Slippery Slope." April 21, 2009. Available at: http://www.dairyherd.com/directories.asp?pgID=675&ed_id=8475.

Dosi, C., and M. Moretto. 1990. "Nonpoint –source pollution control, information asymmetry, and the choice of time profile for environmental fees."

Farzin, Y.H., and P.M Kort. "Pollution Abatement Investment when Environmental Regulation is Uncertain." *Journal of Public Economic Theory.* 2(2000):183-212.

Gay, S.W., D.R. Schmidt, C.J. Clanton, KA. Janni, LD. Jacobson, and S. Weisberg. "Odor, Total Reduced Sulfur, and Ammonia Emissions from Animal Housing Facilities and Manure Storage Units in Minnestoa." *Applied Engineering in Agriculture.* 19,3(2003):347-360.

Hartl, R.F. and P.M Kort. "Capital Accumulation of a Firm Facing an Emissions Tax." *Journal of Economics.* 63(1996):1-23.

Kort. P.M. "Pollution Control and the Dynamics of the Firm: The Effects of Market-Based Instruments on Optimal Firm Investments." *Optimal Control Application and Methods.* 17(1996):267-279.

Koelsch, R., and R. Stowell. Ammonia Emissions Estimator (Daily Version). *University of Nebraska-Lincoln.* January 2009. Available at: http://water.unl.edu/c/document_library/get_file?folderId=67759&name=DLFE-4647.pdf

McDonald, J.A., E.J. O'Donahue, W.D. McBride, R.F. Nehring, C.L. Sandretto, and R. Musheim. Sept. 2007. Profits, Costs, and the Changing Structure of Dairy Farming. ERS Report-47.

Millman, S.R. and R. Prince. "Firm incentives to promote technological innovation in pollution control. *Journal of Environmental Economics and Management.* 17(1989):247-265.

Paulson, Jim. Feeding Dairy Cattle in 2009: Feed Costs and Profitability—"What's in Your Wallet?" *University of Minnesota.* Available at: http://www.extension.umn.edu/forages/pdfs/paulson_iefac_feed_costs_nov_2008.pdf

Rosen, S. "Dynamic Animal Economics." *American Journal of Agricultural Economics.* 69(1987):547-557.

Tarui N., and S. Polasky. "Environmental regulation with technology adoption, learning, and strategic behavior." *Journal of Environmental Economics and Management.* 50(2005):447-467.

United States Environmental Protection Agency (EPA). "Animal Feeding Operations Air Quality Compliance Agreement Information Sheet." March 2009/ Available at: http://www.epa.gov/compliance/resources/agreements/caa/cafo-infosht-0309.html

United States Department of Agriculture (NASS). Agricultural Statistics Board—*National Agricultural Statistics Service.* Livestock Slaughter Data. January 2008.

United States Department of Agriculture-Economic Research Services (NASS/ERS). 2007. Profits, Costs, and the Changing Structure of Dairy Farming. ERR-47. Available at: http://www.ers.usda.gov/publications/err47/err47d.pdf.

United States Department of Agriculture-Agricultural Marketing Services (NASS/ARMS). 2007. Market News and Transportation Data. Dairy Milk Price Data. Available at: http://www.ams.usda.gov/AMSv1.0/ams.fetchTemplateData.do?template=TemplateA&navID=MarketNewsAndTransportationData&leftNav=MarketNewsAndTransportationData&page=DairyCommodityAveragesMain

United States Department of Agriculture-Agricultural Research Service (USDA/ARS), Texas Agrilife Research, Texas Agrilife Extension, Texas A&M University, and West Texas A&M University. 2003-2008. "Air Quality: Reducing Emissions from Cattle Feedlots and Dairies." USDA-CSREES funded projected.

Wolf, C., S. Hanson, E. Wittenberg, and S. Harsh. 2002. Discount rates for dairy farms. Michigan State University Agricultural Economics Staff Paper 02-08.

Xepapadeas, A.P. "Environmental Policy Design and Dynamic Nonpoint-Source Pollution." *Journal of Environmental Economics and Management.* 23(1992):22-39.