Economic Comparison of Liquid Manure Transport and Land Application

J. C. Hadrich, T. M. Harrigan, C. A. Wolf

Abstract. *A spreadsheet-based manure transport and land application decision tool, MANURE$HAUL, was developed to provide farmers, custom applicators, and others involved with manure management a manure cost and labor calculator for liquid manure systems using top-loading tank spreaders and nurse tanks. The manure hauling capacity was a function of the machinery set selected, manure tank capacity, and hauling distance. Manure transport and application costs were a function of spreader tank capacity and hauling distance. Representative 175-, 350-, 700-, and 1,400-cow dairy farms were compared to evaluate hauling time and machinery costs for a range of machinery sets, hauling distances, and nutrient values for the manure applied. Equipment ownership and operating costs were calculated for agitation, pumping, manure transport, land application, and incorporation. Equipment ownership and operating costs ranged from 0.32¢/L of manure hauled per year (1.18¢/gal) for a 175-cow dairy using a 11400-L (3000-gal) spreader with an average hauling distance of 1.6 km (1 mile) and broadcast application with tillage incorporation to 0.50¢/L (1.91¢/gal) for a 1400-cow farm with slurry injection and an average hauling distance of 6.4 km (4 mile) with two 34100-L (9000-gal) spreaders and four nurse trucks for over-the-road transport. Two nurse trucks supplying a tractor-drawn spreader became more cost-effective than two tractor-drawn spreaders alone at a hauling distance of about 4.8 km (3 mile). Injection application increased the number of days needed for manure application compared to a broadcast application with tillage incorporation, but when the time for tillage incorporation was included the total time needed for field operations with injection was less than broadcast with incorporation. Manure injection increased application costs about 6% compared to a broadcast application with tillage incorporation. When high soil phosphorus (P) levels restricted manure application rates to crop P removal rates, the credited nutrient value of the applied manure was reduced by 45%. The credited value of unincorporated manure with soil P constrained by crop removal was reduced by 60% compared to injected slurry with soil P at a build-up level. In each case the value of the manure nutrients applied exceeded the cost of agitation, pumping, transport, land application and incorporation.*

Keywords. *Economics, Manure management, Machinery management, Land application, Tank spreader.*

The need for cost-effective and environmentally sensitive manure application options have caused many livestock farms to transition from daily manure hauling to long-term manure storage. Larger farms with a greater concentration of animals have resulted in increased hauling distances for land application. Applying manure on a limited land base creates a potential for surface and groundwater contamination and inefficient nutrient use. Michigan has adopted best management practices (BMPs) for manure use for continued protection under the Right to Farm Act (Michigan Department of Agriculture, 2008). Best management practices that protect water quality include long-term manure storage, manure application based on soil test results, and limited winter-spreading. The need for cost-effective and environmentally sensitive land application options has caused many farmers to change their manure hauling systems.

Several decision support systems for evaluating livestock manure as a nutrient source have been developed. Koehler et al. (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 and phosphorus limiting applications. Commercial fertilizer prices were used to calculate the value of manure, but 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, five-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 0.0162¢/L-km (0.1¢/gal-mile) for hauling. Manure application rates were not restricted by nitrogen or phosphorous limitations.

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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 feed 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 the interaction of manure handling with feed production on dairy farms. Net return over feed and manure costs was $25/cow at distances greater than 4.8 km (3 mile) using truck-drawn nurse tanks for over-the-road transport.

Current options in manure transport and land application vary greatly in labor, machinery requirements, ownership and operating costs, and compatibility with the environment. If a manure hauling system is poorly designed, delays in manure transport and land application may cause delays in crop tillage and planting, and crop yield and profitability may decline. Harrigan et al. (1996) evaluated the effect of manure hauling systems on timeliness for tillage and planting using DAFOSYM for a 150- and 400-cow dairy in Michigan. Labor availability for land application was constrained to one 10-h day for the 150-cow farm and three 10-h days for the 400-cow farm. Greater labor availability on the 400-cow dairy allowed parallel manure application, tillage, and planting operations and allowed field work to be completed within the time available.

Koelsch et al. (2007) developed a decision support system that included the feeding program, cropping system, and costs associated with the manure hauling system. User inputs included animal numbers, body weight, ration formulation, housing type, 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 were defined by the user and used to calculate field application time, road travel time, set-up time, and manure application rate.

Objectives

A goal of this work was to develop a decision support tool that provided an accurate estimate of cost for manure agitation, pumping, transport and land application, labor requirements, and the nutrient value of manure for crop production. Specific objectives of this work were to:

- 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.
- Validate the model by comparing estimated hauling costs with those reported by two Michigan livestock producers/manure managers.
- Compare costs and labor requirements for liquid manure agitation, pumping, transport, land application and incorporation on representative 175-, 350-, 700- and 1400-cow dairies using tractor-drawn tank spreaders and nurse trucks for over-the-road transport.

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 of top-loading tank spreader systems 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 et al., 1995). MANURE$HAUL is available for use by farmers, consultants and others with an interest in manure management at http://www.ext.nodak.edu/homepages/aedept/staf f/bio_hadrich_j.html.

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, 2010).

Three basic manure hauling systems were considered: (1) tractor-drawn spreader tanks, (2) truck-mounted or truck-drawn spreader tanks, 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.

MANURE$HAUL users can define the type and number of machinery sets used on each farm. For example, a user may select two tractor-drawn spreader tanks working in parallel rather than one tractor-drawn spreader with two truck-drawn nurse trucks. Broadcast application, broadcast application with tillage incorporation, and injection are the three options for land application. Broadcast application with tillage incorporation requires an additional tractor and tillage implement.

Equipment Purchase Price

Purchase prices were collected for four equipment categories: tractors, tank spreaders, agitators and pumps, and tillage equipment for manure incorporation. Purchase price was collected for a range of tractor power (pto-kilowatt, pto-hp) using the on-line “build your own” tractor utility for Case IH and John Deere equipment (Case-IH, 2008; Deere and Co., 2008; table 1). Prices were calculated for 36 diesel-powered, fixed frame (non-articulating) wheeled tractors ranging from 56 to 205 pto-kW (75 to 275 pto-hp). All list prices were for new tractors effective October 2008 (Case-IH, 2008; Deere and Co, 2008; table 1). The purchase price for used tractors was based on auction data for AGCO-Allis, Case-IH, and John Deere tractors (Iron Solutions, 2006; table 1). An average price for 10- to 20-year-old tractors was collected for 116 diesel-powered, fixed frame (non-articulating) wheeled tractors ranging from 56 to 194 pto-kW (75 to 260 pto-hp).

Tank spreader purchase prices were collected from three manufacturers and estimates for truck-mounted and truck-drawn tanks were supplied by custom applicators (table 1). Tank capacities ranged from 6800 to 36000 L (1800 to 9500 gal). Company representatives indicated the most common options selected for the spreader tanks. In Michigan, refurbished gasoline tankers are typically used as nurse trucks 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 tanker was approximately $10,000 plus an additional $15,000 for hydraulics, pumps, and other modifications. The purchase price for a truck-mounted spreader tank was provided by one manufacturer for tanks ranging from 11900 to 18200 L (3150 to 4800 gal). Semi-tractors were used with truck-drawn nurse tank systems. Three custom manure applicators reported using semi-tractors ranging from 5 to 15 years of age with an average age of 10 years at the time of purchase. A representative purchase price was $10,000 with an additional $10,000 investment for hydraulics for the truck.

Farmers generally have three options for liquid manure application: 1) inject manure directly into the soil, 2) surface broadcast, and 3) surface broadcast with incorporation. Injection reduces the number of passes over the field and reduces volatile nitrogen loss but reduces the manure hauling capacity (Harrigan, 2010). Cost information was collected for injection equipment from three custom manure applicators and two spreader tank manufacturers. Mounting a toolbar with injectors and other alterations to a manure spreader was estimated to be $9,000 with an additional $1,600 per injector shank on the toolbar. In MANURE$HAUL, a toolbar with six injectors was used for equipment comparisons. Tractor power was increased by 15 pto-kW (20 pto-hp) compared to a broadcast application when manure was injected.

Incorporating manure into soil requires a tractor and tillage tool. Purchase price data were 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, 2008; Deere and Co., 2008; table 1). All purchase prices were effective October 2008 for 44 tandem disks ranging in width from 3.5 to 10.4 m (11.5 to 34 ft.), 9 combination tools ranging from 3.8 to 5.3 m (12.5 to 17.5 ft.), and 39 field cultivators ranging 5.5 to 18.3 m (18 to 60 ft.).

The purchase price data was used to develop a predictive equation for equipment based on size or capacity:

$$P_i = \beta_0 + \beta_1 X_1 \tag{1}$$

where

P_i is the purchase price of equipment i (i = *NT* for new tractors, *UT* for used tractors, *S* for slurry tank spreader, *TM* for truck mounted spreader, *I* for injector and toolbar, *TD* for tandem disk, *FC* for field cultivator, *CT* for combination tool). β_0 is the intercept β_1 is equipment-specific regression coefficient for X_1.

X_1 is the equipment-specific operational unit [pto-kW (pto-hp) for tractors, rated engine kW (hp) for trucks and semi-tractors, L (gal) for manure tanks and spreaders, number of injection tines for manure injection, implement width in m (ft) for tillage implements].

Ownership Costs

Annual and hourly ownership costs were calculated for tractors, trucks, semi-tractors, tank spreaders, nurse tanks, pumps, agitators, and soil injection and tillage incorporation equipment. Equipment ownership costs included depreciation, interest, housing, and insurance. Straight-line

Table 1. Equipment purchase price functions for trucks, tractors, tank spreaders and tillage implements.

Equipment	P_i	β_0	β_1	X_1	R^{2}[a]
Trucks and tractors					
New	$Price_{NT}$	-32,582	884	$pto\text{-}hp_{NT}$ $pto\text{-}kW_{NT}$	0.90
Used	$Price_{UT}$	7,470	183	$pto\text{-}hp_{UT}$ $pto\text{-}kW_{NT}$	0.43
Semi-tractor	20,000				
Tanks and spreaders					
Slurry tank	$Price_S$	-3,786 (-3,786)	2.91 (11)	LS (gal_S)	0.87
Truck-mounted tank	$Price_{TM}$	68,219 (68,219)	0.63 (2.4)	LTM (gal_{TM})	0.97
Nurse tank	25,000				
Injection unit	$Price_I$	9,000	1,600	Injectors	--
Tillage implements					
Tandem disk	$Price_{TD}$	-884 (-884)	5,117 (1,560)	$widthm_{TD}$ ($widthft_{TD}$)	0.89
Field cultivator	$Price_{FC}$	-2.534 (-3,068)	3,391 (1,125)	$widthm_{TD}$ ($widthft_{FC}$)	0.76
Combination tool[b]	$Price_{CT}$	2,577 (2,404)	5,691 (1,735)	$widthm_{CT}$ ($widthft_{CT}$)	0.84

[a] R^2 is the square of the correlation coefficient between the dependent variable (P_i in eq. 1) and the predicted value from the fitted line.
[b] A combination tool includes a single disk gang, chisel shanks and a rolling harrow to complete soil shattering, leveling and firming in one pass.

depreciation was calculated as the difference between the beginning and ending (salvage) value for a 10-year economic life. Remaining values were based on purchase price, tractor age, and annual hourly use (*ASABE Standards,* 2007a). Remaining value coefficients for agitators and pumps were not provided in the ASABE Standard (D497.5); therefore coefficients for miscellaneous equipment were used.

Tractors were assumed to have a base annual hourly use of 500 hours for new units and 350 hours for used units. Manure hauling hours were added to the base hours for estimating ownership and operating costs. Manure spreader hours were calculated as time needed for manure pumping, transport and land application. Time for pumping and agitation was estimated as the manure pumping time plus sixteen hours for set-up and agitation (eight hours for each of two annual pumping events).

The salvage value of equipment was estimated as:

$$SV_n = (1 - RV_n)*LP \tag{2}$$

where

SV_n = salvage value of equipment in year *n,*

RV_n = remaining value of equipment in year *n,* and

LP = equipment list price.

Housing and insurance were estimated as 0.75%, and 0.25% of the list price of equipment, respectively (*ASABE Standards,* 2007b). The real interest rate was set at 5%.

Operating Costs

Annual operating costs included repairs and maintenance, fuel, lubrication, and labor. Repair and maintenance costs were based on accumulated use (*ASABE Standards,* 2007b). When repair factors were not listed for specific machines, factors for a composite of similar machines were used to best reflect repair and maintenance costs reported by custom manure applicators (table 2). Repair and maintenance cost for injectors was based on information from three custom manure applicators. Repair and maintenance cost was assumed to be $240/injector point for every 405 ha (1000 acre) of use in loam or sandy-loam soil.

Table 2. Repair factors for trucks, manure spreaders, and agitators and pumps (*ASABE Standards*, 2007b).

Equipment	RF1[a]	RF2	Similar Machine
Trucks and tractors			
Small, <60 pto-kW (<80 pto-hp)	0.007	2.0	--
Medium, 60-112 pto-kW (80-150 pto-hp)	0.007	2.0	--
Large, >112 pto-kW (>150 pto-hp)	0.007	2.0	--
Trucks and semi-tractors[b]	0.007	2.0	2 wheel drive and stationary tractor
Manure tanks and spreaders			
Manure spreader[b]	0.16	1.6	Forage wagon and fertilizer spreader
Agitators and pump[b]	0.22	1.8	Forage blower
Tillage incorporation equipment			
Tandem disk	0.180	1.7	--
Field cultivator	0.270	1.4	--
Chisel plow	0.280	1.4	--

[a] *ASABE Standards,* EP496.3 (2007b).
[b] Composite of similar machine repair factors.

Fuel use was estimated as 0.22 L/pto-kW-h (0.044 gal/pto-hp-h) for tractors (*ASABE Standards,* 2007a) and 0.086 L/kW-h (0.0170 gal/hp-h) for semi-tractors and trucks (Harrigan, 2001). Lubrication was estimated as 15% of the fuel cost (*ASABE Standards,* 2007a). Labor was valued at $12/h. Calculated labor hours were increased by 10% to allow additional labor for set-up, scheduled maintenance and other necessary operations. Pumping hours were based on a pumping rate of 7200 L/min (1900 gal/min). Tillage hours were based on machine width, a travel speed of 8 km/h (5 mph), and a field efficiency of 85%. Total hauling cost was the sum of ownership and operating costs.

Nutrient Value of Manure

The value of manure nutrients applied to the land was a function of the nutrient content of manure, quantity of manure applied, and method of application. Tillage incorporation or injection conserves volatile nitrogen and prevents nutrient and contaminant run-off. Injection reduces the odor associated with land application but results in greater downtime for repairs and maintenance of 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.

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 accordingly. 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 converts NH_4^+ to nitrate (NO_3^-) which is subject to loss by leaching and denitrification with subsequent loss to the atmosphere. Volatile ammonia (NH_3) is transformed from NH_4^+ and can be lost to the atmosphere after land application (Jacobs, 1995a,b).

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 losses increase with an increase in temperature and wind speed, and decrease with an increase in relative humidity (Jacobs, 1995b). Organic N becomes available for crop growth over time as it is mineralized to the ammonium form. Available organic N is defined as:

$$\text{Available Organic N} = (\text{Total manure N} - NH_4\text{-N})*m \tag{3}$$

where

Total manure N is the sum of inorganic and organic N fractions, NH_4-N is ammonium N, 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. Subsurface manure injection application resulted in 100% retention of NH_4-N. The amount of NH_4-N retained through surface broadcast application with manure incorporation decreased as the delay between manure application and incorporation increased. Immediate manure incorporation after broadcast application resulted in 70% retention of NH_4-N. Delaying manure incorporation 2-3 days, 4-6 days, and greater than 7 days decreased NH_4-N retention to 40%, 20%, and 10%, respectively.

Fertilizer Recommendations

Fertilizer recommendations for field crops were a function of the crop grown, expected crop yield, soil texture and soil nutrient test levels. Field crop fertilizer recommendations for Michigan, Ohio and Indiana are published in the Tri-State Fertilizer Recommendations (Vitosh et al., 1995) and follow a build-up, maintenance, and draw-down approach to managing soil phosphorus (P). Soil test results below a critical level indicate a nutrient deficiency and a need to "build-up" or raise soil test P levels for optimal crop yield. Critical and maintenance limits vary by crop, soil type, and state (Vitosh et al., 1995). Soil test P at the maintenance level indicates a level of nutrients needed to provide optimal crop yield. Soil test P greater than the maintenance level indicates a surplus and the need to draw-down or reduce P to maintenance levels. For example, for loam soil in Michigan, Bray-1 P soil tests less than 75 parts per million [ppm (mass basis); 165 kg/ha, 150 lb/acre] allow a build-up of soil P whereby manure can be applied at N crop removal rates. Because manure application rates based on crop N removal typically exceed crop P removal, manure application based on N removal results in elevated soil P. Fields testing 75 to 150 ppm (165 to 330 kg/ha, 150 to 300 lb/acre) Bray-1 P are at the maintenance level and manure or commercial P can be applied at P removal rates. Fields testing greater than 150 ppm (330 kg/ha, 300 lb/acre) of soil P require a draw-down of soil P and manure application is not allowed until soil P levels drop below 150 ppm (330 kg/ha, 300 lb/acre).

Fertilizer recommendations in MANURE$HAUL are based on user input for the crop grown and expected yield using the crop nutrient removal guidelines for Michigan field crops (Warncke et al., 2004). The nutrient content of the manure is calculated based on typical values for livestock enterprises (MWPS, 2004) or is provided by the user based on a manure analysis. The quantity of manure nutrients applied was based on the manure application rate and manure analysis. Table 3 presents a summary of Bray-1 P soil test results, fertilizer recommendations, application rates, and nutrient credit guidelines used in MANURE$HAUL.

Table 3. Bray-1 P soil test results, fertilizer recommendations, manure application rates, and nutrient credit guidelines used in MANURE$HAUL.

Bray-1 P	Units	P Management	Application Rate	Nutrient Credits
<75[a]	ppm P	Build-up	N removal	N, P and K
75 to 150	ppm P	Maintenance	P removal	N, P and K up to P removal
>150	ppm P	Draw-down	No application	None

[a] ppm × 2.24 = kg/ha; ppm × 2 = lb/acre (Vitosh et al., 1995).

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. Manure hauling rates were a function of spreader capacity, distance, and the manure hauling system chosen (Harrigan, 2010). Manure was applied with injection, surface broadcast, or surface broadcast with incorporation.

User inputs and default values used in MANURE$HAUL are listed in table 4. Required inputs are: 1) livestock type, 2) number and size of animals (or volume of manure for land application, L, gal), 3) tractor power (pto-kW, pto-hp), spreader volume (L, gal), 4) crop area (ha, acre), crop yield (Mg/ha, ton/acre), 5) soil test results (P and K), and 6) hauling distance (km, mile).

Manure production and nutrient content were based on the user input for the livestock type, size, and number of animals on the farm. Users may accept the default values or use the results of a manure analysis. Tractor, spreader tank, and tillage equipment ownership and operating costs are based on user inputs for tractor size (pto-kW, 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 injector tines.

Users can change default values for fuel price ($/L, $/gal), labor wage rate ($/h), fertilizer prices ($/kg, $/lb N, P and K), and the depreciation schedule of equipment (5-10 years). Parameters that cannot be changed are fuel use (L/pto-kW-h, gal/pto-hp-h), annual tractor use (hours), real interest rate, housing, and insurance.

As farms consolidate and increase in size, they typically acquire a land base of increasing distance for manure transport. 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 using one tractor, one spreader tank and one operator is an efficient system when hauling within a few km (miles) 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.

Table 4. MANURE$HAUL user inputs, default values, and override options.

Parameter	User Input	Default Value	Override[a]	
Animals and manure			Yes	No
Beef, dairy, swine[b]	Number of animals	--	X	--
Manure analysis	$N\text{-}P_2O_5\text{-}K_2O$ kg/1,000 L (lb/1,000 gal)	--	X	--
Manure production	L (gal)	--	X	--
Equipment				
Tractors[b]	pto-kW (pto-hp)	--	X	--
Trucks[b]	kW (hp)	--	X	--
Spreader and nurse tanks[b]	capacity, L (gal)	--	X	--
Injectors[b]	number	6	X	--
Tillage equipment[b]	width, m (ft)	--	X	--
Tractor fuel use	L (gal)	0.22 L/ pto-kW-h (0.044 gal/pto-hp-h)	--	X
Truck fuel use	L (gal)	0.086 L/kW-h (0.0170 gal/pto-hp)	--	X
New tractor annual use	h	500	--	X
Used tractor annual use	h	350	--	X
Crop area[b]				
Zones (1-4)	Yield, unit/ha (unit/acre)	--		
	Hauling distance, km (mile)	--		
	Soil test results	--		
Economic parameters				
Diesel fuel price	\$/L (\$/gal)	\$0.46/L (\$1.75/gal)	X	--
Labor wage rate	\$/h	\$12/h	X	--
Fertilizer prices				
N	\$/kg (\$/lb)	\$1.43/kg (\$0.65/lb)	X	--
P_2O_5	\$/kg (\$/lb)	\$2.03/kg (\$0.92/lb)	X	--
K_2O	\$/kg (\$/lb)	\$1.65/kg (\$0.75/lb)	X	--
Economic life	Years	5-10	X	--
Real interest rate	%	5%	--	X
Taxes[c]	% of machinery list price	1%, not applicable in MI	X	--
Housing	% of machinery list price	0.75%	--	X
Insurance	% of machinery list price	0.25%	--	X

[a] "Override" means the user can input preferred values.
[b] Required user input values.
[c] In Michigan, machinery tax is not applicable. MANURE$HAUL user default value is 1% of machinery list price for states that assign machinery tax.

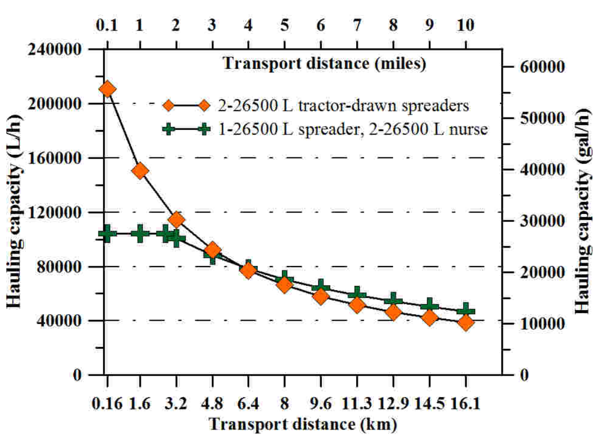

Figure 1. Hauling capacity of two 26500-L (7000-gal) tractor-drawn tank spreaders working in parallel and one 26500-L (7000-gal) tractor-drawn spreaders in parallel with two 26500-L (7000-gal) nurse trucks for up to 16.1-km (10-mile) hauling distance.

Tractor-drawn spreaders have a hauling rate advantage compared to spreader tank/nurse truck systems 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. 1). The hauling capacity with a 4.8 km (3 mile) haul is less than one-half that when hauling near the 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 travel speed.

Manure Hauling on Representative Dairy Farms

Many of the questions that manure managers have regarding farming systems relate to capacity, cost, and labor requirements of the manure hauling system. Land application methods used in MANURE$HAUL include surface broadcast, or subsurface injection with tractor-drawn tank spreaders, and surface broadcast with truck-mounted or truck-drawn tank spreaders. The ability of MANURE$HAUL to describe, evaluate and compare a range of manure transport and land application options was demonstrated with hauling systems on four representative 175-, 350-, 700- and 1400-cow dairy farms (table 5).

The land available for each farm was 1.2 ha (3 acres) per cow with a cropping program of corn grain, corn silage, and

Table 5. Farm characteristics for 175-, 350-, 700-, and 1400-cow dairies.

	175-cow Dairy	350-cow Dairy	700-cow Dairy	1400-cow Dairy
Animals				
Dairy cows	175	350	700	1,400
Dry cows	35	70	140	280
Heifers	88	175	350	700
Manure volume[a], 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)
Manure nutrients				
N, kg (lb)	36,100 (79,515)	72,150 (158,921)	144,300 (317,842)	288,601 (635,684)
P_2O_5, kg (lb)	17,408 (38,343)	34,799 (76,650)	69,598 (153,300)	139,196 (306,600)
K_2O, kg (lb)	22,964 (50,582)	45,877 (101,050)	91,754 (202,101)	183,507 (404,201)
Crop area, ha (acre)				
Zone 1: Corn silage	20.6 (51)	40.9 (101)	81.8 (202)	163.5 (404)
Zone 2: Corn silage	20.6 (51)	40.9 (101)	81.8 (202)	163.5 (404)
Zone 3: Corn grain	30.8 (76)	61.5 (152)	123 (304)	246.1 (608)
Zone 4: Corn grain	30.8 (76)	61.5 (152)	123 (304)	246.1 (608)
Manure hauling distance, km (mile)				
Zone 1: Corn silage	0.4 (0.25)	0.8 (0.5)	1.2 (0.8)	1.6 (1.0)
Zone 2: Corn silage	0.8 (0.5)	1.6 (1.0)	1.9 (1.2)	2.4 (1.5)
Zone 3: Corn grain	2.4 (1.5)	2.4 (1.5)	3.4 (2.1)	4.0 (3.0)
Zone 4: Corn grain	3.2 (2.0)	5.0 (3.1)	5.0 (3.1)	6.4 (4.0)
Farm average	1.6 (1.0)	2.4 (1.5)	3.2 (2 .0)	4.2 (2.6)

[a] Annual manure production for cows plus replacements.

alfalfa on loam soil (Wittenberg and Wolf, 2005). The area allocated to corn grain, alfalfa, and corn silage was typical for Michigan farms with 50% of the area in alfalfa and the remaining land in corn (Hadrich et al., 2008). Sixty percent of the corn land area was harvested as 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 nutrients available in the soil before the crop is planted and allow the farmer to determine if the soil is at a level requiring build-up, maintenance, or draw-down of soil P. Fertilizer recommendations based on crop nutrient removal for optimal crop yield were estimated from yield goals for corn grain and corn silage (table 6; Warncke et al., 2004).

Machinery sets were selected to complete manure hauling in approximately 15 to 20 10-h calendar days (Harrigan, 2001). Individual fields were aggregated into zones based on hauling distance to decrease the number of inputs in MANURE$HAUL. For example, a farm with four fields of varying area planted in corn grain within 1.6 km (1 mile) of the manure storage facility were aggregated in one field zone with an average hauling distance of 1.6 km (1 mile; table 5). The machinery sets selected were not necessarily optimal

Table 6. Nutrient removal and soil test results for corn and alfalfa crops.

Crop	Yield	N	P_2O_5	K_2O
		Nutrient Removal, kg/ha (lb/acre)		
Corn grain	8.1 Mg/ha (130 bu/acre)	131 (117)	54 (48)	39 (35)
Corn silage	33.6 Mg/ha (15 ton/acre)	158 (141)	56 (50)	134 (120)
Alfalfa hay	13.4 Mg/ha (6 ton/acre)	302 (270)	87 (78)	336 (300)
	Units	Soil Test Results, kg/ha (lb/acre)		
Corn grain	kg/ha (lbs/acre)	45 (40)	90 (80)	112 (100)
Corn silage	kg/ha (lbs/acre)	78 (70)	90 (80)	157 (140)

or least-cost systems, rather machinery sets that would likely be used with farms of that size in the Great Lakes region. An average hauling distance to all zones was 1.6 km (1 mile) for the 175-cow dairy farm and 2.4, 3.2, and 4.8 km (1.5, 2, and 2.5 mile) for the 350-, 700- and 1400-cow dairy farms, respectively. Purchase prices for the machinery sets chosen are listed in table 7.

Results and Discussion

The productivity of tractor-drawn tank spreaders decreased rapidly as transport distance increased. Compared to hauling near storage, the hauling capacity of two 26500-L (7000-gal) tank spreaders decreased by more than 50% with a 4.8-km (3-mile) haul (fig. 1). Two nurse trucks for over-the-road transport to a tank spreader reduced the hauling capacity near storage, but improved transport efficiency with longer hauls.

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 farm using: 1) two 34,100 L (9000 gal) tractor-drawn spreaders, and 2) one 34,100 L (9000 gal) tractor-drawn spreader in the field with two 34,100 L (9000 gal) truck-drawn nurse tanks for over-the-road transport. The hauling distance was varied from 0.8 to 12.9 km (0.5 to 8 mile) when hauling 23.8 million L (6.1 million gal) for broadcast application. Based on cost and labor requirements for manure transport and land application, truck-drawn nurse tank-based systems had an advantage when the hauling distance was greater than 4.8 km (3 mile). Two tractor-drawn spreaders working in parallel had a lower cost 0.20 to 0.29¢/L (0.72 to 1.11¢/gal) than one tractor-drawn spreader with two nurse trucks, 0.29 to 0.30¢/L (1.11 to 1.14¢/gal) when land application was within 4.8 km (3 mile) of storage (fig. 2). Beyond 4.8 km (3 mile) the cost for the two tractor-drawn spreaders increased

Table 7. Equipment purchase prices for representative 175-, 350-, 700-, and 1400-cow dairy farms.

	175-cow Dairy		350-cow Dairy		700-cow Dairy		1400-cow Dairy	
	Size	Purchase Price ($)	Size	Purchase Price ($)	Size	Purchase Price ($)	Size	Purchase Price ($)
Broadcast application								
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
Semi-tractor, kW (hp)	--	--	--	--	--	--	298 (400)	50,000
Spreader tank, L (gal)	11,400 (3,000)	25,978	28,400 (7,500)	71,195	34,100 (9,000)	86,268	34,100 (9,000)	86,268
Nurse tank, kW (hp)	--	--	--	--	--	--	2-34,100 (2-9,000)	25,000
Lagoon pump	Medium	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
Injector tines (number)	6	18,600	6	18,600	6	18,600	6	18,600

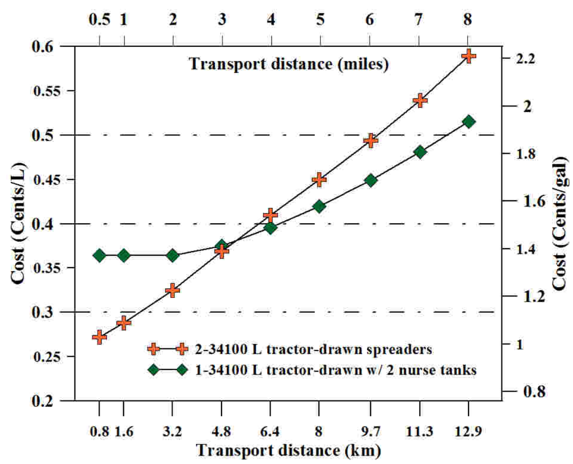

Figure 2. Manure transport and application costs for two 34,100-L (9000-gal) tractor-drawn spreaders and one 34,100-L (9000-gal) tractor-drawn spreader with two 34,100-L (9000-gal) nurse tanks.

from 0.33 to 0.52¢/L (1.25 to 1.95¢/gal) with a 12.8-km (8-mile) haul while the cost for the tractor-drawn/nurse truck system increased to 0.44¢/L (1.68¢/gal) with a 12.8-km (8-mile) haul. The cost-effective switch from tractor-drawn to nurse truck/spreader-tank systems occurred at about 4.8 km (3 miles) which was consistent with the experience of custom applicators in the Great Lakes region.

MANURE$HAUL was used to estimate manure hauling costs and labor requirements for representative 175-, 350-, and 700-cow dairy farms (table 8) using broadcast, broadcast with incorporation, and subsurface injection.

Broadcast with Tillage Incorporation

The farm average hauling rate ranged from 38,554 L/h (10,186 gal/h, 175-cow dairy) to 141,070 L/h (37,271 gal/h, 700-cow dairy) (table 9). The labor for manure pumping, transport, and application was 16.6, 20.0, and 18.7 days for the 175-, 350-, and 700-cow dairy farms, respectively. Additional time needed for manure incorporation with a tandem disk ranged from 3.1 days with the 175-cow dairy to 6.8 days with the 700-cow dairy on an annual basis.

The ownership and operating costs for manure agitation and pumping ranged from $83.78/h for the 175-cow dairy farm with a medium capacity lagoon pump to $194.51/h for the 700-cow dairy farm using two large lagoon pumps (table 9). Pumping and agitation costs were charged to the operation only for the time the equipment was in use. Transport and land application of manure hauled per year accounted for about two-thirds of the total cost and ranged from 0.21¢/L (0.78¢/gal) for the 175-cow dairy to 0.27¢/L (1.03¢/gal) for the 700-cow dairy farm. The total cost including pumping, agitation, and tillage incorporation ranged from 0.31¢/L, (1.18¢/gal) for the 175-cow dairy farm to 0.36¢/L (1.38¢/gal) for the 700-cow dairy farm. Pumping, agitation, and tillage incorporation accounted for about one-third of the total cost. The cost for tillage incorporation was somewhat greater for the 175-cow dairy farm because the tandem disk was larger relative to the land base compared to the 350- and 700-cow farms.

Subsurface Injection

The labor requirement for slurry injection was similar to a broadcast with tillage incorporation. Excluding tillage incorporation, slurry injection increased the time needed for transport and land application by 13% to 19% (table 10). When the additional time needed for tillage incorporation with a single pass of a tandem disk was included, slurry injection decreased the time needed for field operations by 2.8 days for the 700-cow dairy and less than one day for the 175- and 350-cow dairies.

When including only transport and application, the costs for slurry injection increased from 21% (700-cow dairy farm) to 36% (175-cow dairy farm) compared to surface broadcast; however, when the costs for pumping, agitation, and tillage incorporation were included the total cost for slurry injection was only about 2% to 3% greater on the 175- and 350-cow farms and 7% greater on 700-cow dairy farm (table 10). Transport and injection accounted for about 85% of the total cost with pumping and agitation accounting for about 15%. The cost for transport and land application ranged from 0.28¢/L of manure hauled per year (1.06¢/gal) for the 175-cow dairy farm to 0.33¢/L (1.25¢/gal) for the 700-cow dairy farm. Total costs ranged from 0.32¢/L (1.22¢/gal) on the 175-cow farm to 0.39¢/L (1.47¢/gal) on the 700-cow farm.

Table 8. Machinery complement and hauling distance for three representative dairy farms.

	175-cow Dairy	350-cow Dairy	700-cow Dairy
Manure volume, L (gal)[a]	5,781,822 (1,527,562)	11,554,038 (3,052,586)	23,108,079 (6,105,173)
Machinery set	1 tractor-drawn	1 tractor-drawn	2 tractor-drawn
Hauling distance, km (mile)			
Zone 1: Corn silage	0.4 (0.25)	0.8 (0.5)	1.2 (0.8)
Zone 2: Corn silage	0.8 (0.5)	1.6 (1.0)	1.9 (1.2)
Zone 3: Corn grain	2.4 (1.5)	2.4 (1.5)	3.4 (2.1)
Zone 4: Corn grain	3.2 (2.0)	5.0 (3.1)	5.0 (3.1)
Average hauling distance	1.6 (1.0)	2.4 (1.5)	3.2 (2.0)

[a] Annual manure production for cows plus replacements.

Table 9. Annual machinery, labor, and costs for manure agitation, pumping, transport and broadcast application with tillage incorporation on three representative dairy farms.

	175-cow Dairy	350-cow Dairy	700-cow Dairy
Pumping and agitation			
Tractor, pto-kW (pto-hp)	75 (100)	127 (170)	127 (170)
Lagoon pump (size)	Medium	Large	2 Large
Pumping and agitation, h	29	43	70
Manure hauling			
Spreader tractor, pto-kW (pto-hp)	89 (120)	164 (220)	2-179 (240)
Spreader tank, L (gal)	11,400 (3,000)	28,400 (7,500)	2-34,100 (9,000)
Hauling rate, L/h (gal/h)			
Zone 1: Corn silage	45,149 (11,928)	80,851 (21,361)	172,471 (45,567)
Zone 2: Corn silage	42,339 (11,186)	71,102 (18,785)	153,635 (40,591)
Zone 3: Corn grain	32,744 (8,651)	62,528 (16,520)	121,910 (32,209)
Zone 4: Corn grain	28,795 (7,608)	41,447 (10,950)	94,281 (24,909)
Farm average hauling rate, L/h (gal/h)	38,554 (10,186)	66,380 (17,524)	141,070 (37,271)
Tillage incorporation			
Tractor, pto-kW (pto-hp)	104 (140)	134 (180)	134 (180)
Tandem disk, m (ft)	5.5 (18)	7.6 (25)	9.8 (32)
Labor, h (10 h-days)[a]			
Pumping, transport and application	183 (18.3)	228 (22.8)	412 (20.6)[b]
Tillage incorporation[c]	31 (3.1)	44 (4.4)	68 (6.8)
Labor per cow, h	1.0	0.7	0.6
Cost			
Agitation and pumping			
$/h	83.78	118.34	194.51
¢/L (¢/gal)	0.04 (0.16)	0.04 (0.17)	0.06 (0.22)
Transport and application			
$/h	65.13	128.50	303.17
¢/L (¢/gal)	0.21 (0.78)	0.25 (0.96)	0.27 (1.03)
Tillage incorporation			
$/h	116.04	129.64	120.82
¢/L (¢/gal)	0.06 (0.24)	0.05 (0.19)	0.04 (0.13)
$/ha ($/acre)	5.79 (14.30)	4.57 (11.28)	3.29 (8.13)
Total cost			
¢/L (¢/gal)	0.31 (1.18)	0.35 (1.31)	0.36 (1.38)
$/ha ($/acre)[d]	29.93 (73.93)	32.02 (79.10)	31.03 (76.66)
$/cow[e]	102.81	114.35	110.82

[a] Calculated labor hours were increased by 10% to allow additional time for scheduled maintenance and related activities. Calculated labor included time for manure transport, land application and tillage, plus 16 hours for pump set-up and agitation.
[b] 206 hours were required for each spreader tractor complement on the 700-cow dairy.
[c] Average field speed of 7.48 km/h (4.65 mile/h).
[d] Total annual cost divided by the field area to which manure was applied.
[e] Average annual cost per lactating cow.

Table 10. Annual machinery, labor, and costs for manure agitation, pumping, transport, and subsurface injection on three representative dairy farms.

	175-cow Dairy	350-cow Dairy	700-cow Dairy
Manure hauling			
Spreader tractor, pto-kW (pto-hp)	112 (150)	179 (240)	2-194 (2-260)
Spreader tank, L (gal)	11,400 (3,000)	28,400 (7,500)	2-34,100 (2-9,000)
Injector	6-point	6-point	6-point
Hauling rate, L/h (gal/h)			
Zone 1: Corn silage	38,928 (10,285)	66,077 (17,458)	140,132 (37,023)
Zone 2: Corn silage	36,726 (9,703)	58,810 (15,538)	126,183 (33,338)
Zone 3: Corn grain	29,092 (7,686)	52,343 (13,829)	102,313 (27,031)
Zone 4: Corn grain	25,893 (6,841)	36,054 (9,525)	81,047 (21,413)
Farm average hauling rate, L/h (gal/h)	33,693 (8,901)	55,145 (14, 569)	116,556 (30,797)
Labor, h (10 h-days)[a]			
Pumping, transport and application[b]	206 (20.6)	268 (26.8)	492 (24.6)[c]
Labor per cow, h	1.2	0.8	0.7
Cost			
Agitation and pumping			
$/h	83.78	118.34	194.51
¢/L (¢/gal)	0.04 (0.16)	0.04 (0.17)	0.06 (0.22)
Transport application			
$/h	85.19	139.47	311.47
¢/L (¢/gal)	0.28 (1.06)	0.31 (1.18)	0.33 (1.25)
Total cost			
¢/L (¢/gal)	0.32 (1.22)	0.35 (1.34)	0.39 (1.47)
$/ha ($/acre)[d]	29.73 (73.44)	32.84 (81.12)	32.71 (80.81)
$/cow[e]	106.58	117.27	116.82

[a] Calculated labor hours were increased by 10% to allow additional time for scheduled maintenance and related activities. Calculated labor included time for manure transport, land application, and tillage, plus 16 h for pump set-up and agitation.
[b] Average field speed of 8 km/h (5 mile/h).
[c] 246 h were required for each spreader tractor complement on the 700-cow dairy.
[d] Total annual cost divided by the field area to which manure was applied.
[e] Average annual cost per lactating cow.

The costs for slurry injection were slightly greater than for broadcast with tillage incorporation but the labor requirement for injection was slightly less. Injection required more time for transport and application, but broadcast required an additional tractor and operator for timely manure incorporation. Injection improves N retention and reduces the potential for odor nuisance complaints. Farm managers must balance labor, costs, timeliness of field operations and equipment availability with the potential for N retention and odor reduction in the cropping system.

Manure Pumping and Land Application on 1400-Cow Dairies

Machinery complement and transport distance were varied on four representative 1400-cow dairies to evaluate labor requirements and costs for manure agitation, pumping, transport, and land application (table 11). Four 34100-L (9000-gal) tractor-drawn spreaders working in parallel were used on Farms 1 and 3. High-speed tractors with an average over-the-road travel speed of about 39 km/h (24 mph) were used to increase hauling capacity. Two 34100-L (9000-gal) tractor-drawn spreaders were used on Farms 2 and 4 for over-the-road transport to fields within 4.8 km (3 mile), and four 34100-L (9000-gal) nurse trucks were used for over-the-road transport to the two tractor-drawn spreaders when fields were more than 4.8 km (3 mile) from storage. The average transport distance for farms 1 and 2 was 4.2 km (2.5 mile). The average transport distance was increased by 60% to 6.4 km (4 mile) for Farms 3 and 4 with no change to the machinery complement.

Broadcast Application

The hauling capacity within 4.8 km (3 mile) of storage for Farm 1 with four tractor-drawn spreaders was two times the capacity of Farm 2 where only two tractor-drawn spreaders were used. When hauling greater than 4.8 km (3 mile) the hauling capacity of two tractor-drawn spreaders with four nurse trucks was equivalent to four tractor-drawn spreaders alone (fig. 1, table 12), but the loss of hauling capacity near storage with the nurse truck-based system reduced the overall hauling capacity about 36%. The annual time needed for pumping and land application was 868 h (21.7 10-h days, 0.6 h/cow-yr) with the four tractor-drawn spreaders (Farm 1) and 1214 h (28.1 10-h days, 0.9 h/cow-yr) with the tractor spreader/nurse truck system (Farm 2). An additional 13.6 10-h days (0.1 h/cow-yr) were needed for manure incorporation with a tandem disk.

Farms 3 and 4 used the same machinery complement as Farms 1 and 2, respectively, but with a 60% increase in the average hauling distance from 4.1 to 6.5 km (2.5 to 4 miles, table 12). A 60% increase in the hauling distance reduced the hauling capacity 10% to 15% when hauling to crop zones 1 and 2 within 4.8 km (3 mile) of storage, and about 19% when hauling greater than 4.8 km (3 miles). The overall hauling

Table 11. Farm characteristics and equipment used for broadcast and injection application on four representative 1400-cow dairy farms.

	Farm 1	Farm 2	Farm 3	Farm 4
Manure volume				
L (gal)[a]	46,216,155 (12,210,345)	46,216,155 (12,210,345)	46,216,155 (12,210,345)	46,216,155 (12,210,345)
Machinery set[b]	4 tractor-drawn spreaders	2 tractor-drawn spreaders <4.8 km (3 mile), 2 tractor-drawn spreaders with 4 nurse tanks ≥ 4.8 km (3 mile)	4 tractor-drawn spreaders	2 tractor-drawn spreaders <4.8 km (3 mile), 2 tractor-drawn spreaders with 4 nurse tanks ≥4.8 km (3 mile)
Hauling distance, km (mile)				
Zone 1: Corn silage	1.6 (1.0)	1.6 (1.0)	2.4 (1.5)	2.4 (1.5)
Zone 2: Corn silage	2.4 (1.5)	2.4 (1.5)	3.7 (2.3)	3.7 (2.3)
Zone 3: Corn grain	4.0 (3.0)	4.0 (3.0)	7.2 (4.5)	7.2 (4.5)
Zone 4: Corn grain	6.4 (4.0)	6.4 (4.0)	9.6 (6.0)	9.6 (6.0)
Average hauling distance	4.2 (2.5)	4.2 (2.5)	6.4 (4.0)	6.4 (4.0)
Pumping and agitation				
Tractor, pto-kW (pto-hp)	127 (170)	127 (170)	127 (170)	127 (170)
Lagoon pump (size)	2 Large	2 Large	2 Large	2 Large
Pumping and agitation, h	123	123	123	123
Manure hauling				
Spreader tank, L (gal)	4-34,100 (4-9,000)	2-34,100 (2-9,000)	4-34,100 (4-9,000)	2-34,100 (2-9,000)
Nurse tank, L (gal)	--	4-34,100 (4-9,000)	--	4-34,100 (4-9,000)
Truck, kW (hp)	--	4-298 (4-400)	--	4-298 (4-400)

[a] Annual manure production for cows plus replacements.
[b] High-speed tractors were used to increase hauling capacity.

capacity decreased 15%. The annual labor requirement for manure pumping, transport and application was 1052 h (26.3 10-h days, 0.8 h/cow-yr) for Farm 3 and 1394 h (26.3 10-h days, 1.0 h/cow-yr) for Farm 4.

There was little difference in the hourly cost for transport and application between the four farms (about \$565 to \$606/h, table 12), but differences in hauling system productivity lead to large differences in transport and land application costs. The farm average hauling rate for Farm 1 with four tractor spreaders was 56% greater than the tractor spreader/nurse truck system (Farm 2), and the average cost for transport and application of manure hauled per year for Farm 2 (0.37¢/L, 1.40¢/gal) was 32% greater than for Farm 1 (0.28¢/L, 1.06¢/gal). A 60% increase in the hauling distance for the four tractor-drawn spreaders increased the average transport and land application cost about 15% to 0.32¢/L (1.22¢/gal).

The nurse truck-based system was less sensitive to an increase in hauling distance than the tractor-spreader system. A 60% increase in the hauling distance for Farm 2 decreased productivity about 16% (Farm 4) and increased the hauling cost about 12%. Total costs for agitation, pumping, transport, land application, and incorporation with a single pass with a tandem disk increased 25% from 0.35¢/L (1.34¢/gal) for Farm 1 with four tractor-drawn spreaders to 0.44¢/L (1.68¢/gal) for Farm 2 with the tractor-spreader/nurse truck system. A 60% increase in the hauling distance increased the total cost for each system about 10%. Manure transport and land application accounted for about 80% to 85% of the total cost for agitation, pumping, land application, and manure incorporation.

Subsurface Injection

Manure was injected with a six-point injector mounted on the rear of the spreader tank. The slurry discharge rate was 5110 L/min (1350 gpm), about one-half the discharge rate of a broadcast application. Compared to a broadcast application, injection requires additional time for such tasks as replacing, repairing, or unplugging injectors. The lower discharge rate and additional time for repair and maintenance reduce the hauling capacity compared to a broadcast application.

Subsurface injection reduced the hauling capacity of Farms 1 and 2 about 25% compared to a broadcast application within 4.8 km (3 mile) of storage (table 13). The reduction in hauling capacity diminished with longer hauls with the tractor-drawn spreaders (Farm 1) and reduced the hauling capacity by 15% to 20% when fields were greater than 4.8 km (3 mile) from storage. Injection did not reduce the hauling capacity of Farm 2 when hauling greater than 4.8 km (3 mile) because the tractor-drawn spreaders experienced idle time in waiting for the nurse trucks to arrive so the lower discharge rate did not limit system capacity.

Injection increased the time needed for land application by three to four days compared to broadcast with incorporation on Farms 1 and 2 (table 13). The farm average hauling rate on Farm 1 was about 20% lower with injection compared to broadcast with incorporation. Transport and application productivity only dropped about 7% for Farm 2 with the nurse-truck based system. The annual labor per cow plus replacements for manure agitation, pumping, transport and application was 0.6 h/cow-yr on Farm 1 with broadcast and incorporation and 0.7 h/cow-yr with injection. Labor on Farm 2 was 0.7 h/cow-yr for both injection and broadcast with incorporation.

Table 12. Annual machinery, labor, and costs for manure agitation, pumping, transport, and broadcast application on representative 1400-cow dairy farms.

	Farm 1	Farm 2	Farm 3	Farm 4
Manure hauling				
Spreader tractor, pto-kW (pto-hp)	4-179 (4-240)	2-179 (2-240)	4-179 (4-240)	2-179 (2-240)
Hauling rate, L/h (gal/h)				
Zone 1: Corn silage	341,723 (90,283)	170,861 (45,142)	305,821 (80,798)	152,910 (40,399)
Zone 2: Corn silage	305,821 (80,798)	152,910 (40,399)	258,915 (68,406)	128,028 (33,825)
Zone 3: Corn grain	214,391 (56,642)	205,663 (54,336)	174,426 (46,084)	179,070 (47,310)
Zone 4: Corn grain	183,920 (48,592)	188,148 (49,709)	148,785 (39,309)	154,382 (40,788)
Farm average hauling rate, L/h (gal/h)	273,295 (72,371)	182,925 (48,329)	234,063 (61,839)	156,244 (41,280)
Tillage incorporation				
Tractor, pto-kW (pto-hp)	134 (180)	134 (180)	134 (180)	134 (180)
Tandem disk, m (ft)	9.8 (32)	9.8 (32)	9.8 (32)	9.8 (32)
Labor, hours (10 h-days)				
Pumping, transport and application[a]	868 (21.7)[b]	1,214 (28.1)[c]	1,052 (26.3)[d]	1,394 (33.0)[e]
Tillage incorporation[f]	136 (13.6)	136 (13.6)	136 (13.6)	136 (13.6)
Labor per cow, h	0.6	0.9	0.8	1.0
Cost				
Agitation and pumping				
$/h	165.29	165.29	165.29	165.29
¢/L (¢/gal)	0.04 (0.17)	0.04 (0.17)	0.04 (0.17)	0.04 (0.17)
Transport and application				
$/h	596.61	605.93	564.99	582.92
¢/L (¢/gal)	0.28 (1.06)	0.37 (1.40)	0.32 (1.22)	0.41 (1.57)
Tillage incorporation				
$/h	96.16	96.16	96.16	96.16
¢/L (¢/gal)	0.03 (0.11)	0.03 (0.11)	0.03 (0.11)	0.03 (0.11)
Total cost				
¢/L (¢/gal)	0.35 (1.34)	0.44 (1.68)	0.39 (1.49)	0.49 (1.85)
$/ha ($/acre)[g]	30.57 (75.50)	41.01 (101.03)	34.38 (84.91)	45.28 (111.84)
$/cow[h]	116.42	145.93	130.02	161.57

[a] Calculated labor hours were increased by 10% to allow additional time for scheduled maintenance and related activities. Calculated labor included time for manure transport, land application and tillage, plus 16 hours for pump set-up and agitation.
[b],[d] 217 hours were required for each spreader tractor complement for Farm 1, and 263 hours for Farm 3.
[c] 125 hours were required for each spreader tractor complement hauling distances less than 4.8 km (3 mile), and 155 hours for each spreader tractor complement with 2 nurse trucks hauling distance greater than 4.8 km (3 mile).
[e] 145 hours were required for each spreader tractor complement hauling less than 4.8 km (3 mile), and 184 hours for each spreader tractor complement with 2 nurse trucks hauling distance greater than 4.8 km (3 mile).
[f] An average field speed of 7.48 km/h (4.65 mile/h).
[g] Total annual cost divided by the total field area to which manure was applied.
[h] Average annual cost per lactating cow.

The cost for manure transport and injection was 0.35¢/L (1.31¢/gal) for Farm 1 when hauling an average of 4.1 km (2.5 mile) with four tractor-drawn spreaders was 24% higher than transport and broadcast application without incorporation, but the total cost for agitation, pumping, transport, and subsurface injection (0.39¢/L, 1.48¢/gal) was only 10% greater than a broadcast application with tillage incorporation (0.35¢/L, 1.34¢/gal; table 13). When the hauling distance was increased by 60% the total cost increased about 11% for both Farms 1 and 2. The total cost for the nurse truck-based system on Farm 2 (0.45¢/L, 1.72¢/gal) 16% greater than the tractor-drawn spreader-based system on Farm 1 (0.39¢/L, 1.48¢/gal).

Return on Manure Nutrient Value

The effect of varying manure application method (injection, broadcast, and broadcast with next-day incorporation) and varying soil test P levels (P build-up, maintenance, or draw-down) on the cost of manure agitation, pumping, transport, and land application on a representative, 1400-cow dairy (Farm 1, tables 11-13) was evaluated. The manure nutrient value was based on a manure analysis and current prices for commercial N, P and K. The manure analysis was 2.88 kg/1000 L (24 lb/1000 gal) N; 2.16 kg/1000 L (18 lb/1000 gal) P; and 3.48 kg/1000 L (29 lb/1000 gal) K. Fertilizer recommendations were based on crop nutrient removal and expected crop yield (Table 14). Manure slurry was applied at 56,432 L/ha (6033 gal/acre) and manure nutrients were valued at $1.43/kg ($0.65/lb) N, $2.03/kg (0.92/lb) P, and $1.65/kg (0.75/lb) K.

The value of manure N, P, and K was 1.3¢/L (4.8¢/gal). Phosphorus and potassium are fairly stable in the soil and are generally not subject to leaching, volatilization, or other losses. The ammonium fraction of manure N can be quickly converted to ammonia and lost to the atmosphere, and N in nitrate form can be leached from the root zone. When the soil

Table 13. Annual machinery, labor, and costs for manure agitation, pumping, transport, and subsurface injection on four representative 1400-cow dairy farms.

	Farm 1	Farm 2	Farm 3	Farm 4
Manure hauling				
Spreader tractor, pto-kW (pto-hp)	194 (260)	2-194 (2-260)	194 (260)	2-194 (2-260)
Spreader tank, L (gal)	4-34,065 (4-9,000)	2-34,065 (2-9,000)	4-34,065 (4-9,000)	2-34,065 (2-9,000)
Truck, kW (hp)	--	4-298 (2-400)	--	4-298 (2-400)
Nurse tank, L (gal)	--	4-34,100 (2-9,000)	--	4-34,100 (2-9,000)
Hauling rate, L/h (gal/h)				
Zone 1: Corn silage	268,591 (70,962)	134,296 (35,481)	243,031 (64,209)	121,516 (32,105)
Zone 2: Corn silage	243,031 (64,209)	121,516 (32,105)	209,179 (55,265)	103,549 (27,358)
Zone 3: Corn grain	180,042 (47,567)	205,663 (54,336)	153,798 (40,634)	179,070 (47,310)
Zone 4: Corn grain	161,765 (42,738)	188,148 (49,709)	132,177 (34,921)	154,382 (40,788)
Farm average hauling rate, L/h (gal/h)	221,824 (58,612)	155,505 (43,084)	192,858 (50,953)	145,091 (38,333)
Labor, hours (10-h days)				
Pumping, transport and application[a],[b]	1,040 (26.0)[e]	1,250 (31.4)[f]	1,224 (30.6)[g]	1,468 (36.6)[h]
Labor per cow, h	0.7	0.9	0.9	1.0
Cost				
Agitation and pumping				
$/h	165.29	165.29	165.29	165.29
¢/L (¢/gal)	0.04 (0.17)	0.04 (0.17)	0.04 (0.17)	0.04 (0.17)
Transport and application				
$/h	614.69	600.75	589.70	582.50
¢/L (¢/gal)	0.35 (1.31)	0.41 (1.55)	0.39 (1.47)	0.46 (1.74)
Total cost				
¢/L (¢/gal)	0.39 (1.48)	0.45 (1.72)	0.43 (1.64)	0.50 (1.91)
$/ha ($/acre) [c]	34.06 (84.13)	42.57 (105.14)	38.08 (94.06)	47.38 (117.04)
$/cow[d]	128.90	152.00	143.25	169.21

[a] Calculated labor hours were increased by 10% to allow additional time for scheduled maintenance and related activities. Calculated labor included time for manure transport, land application and tillage, plus 16 hours for pump set-up and agitation.
[b] An average field speed of 8 km/h (5 mile/h).
[c],[e] 235 hours were required for each spreader tractor complement for Farm 1, and 277 hours for Farm 3.
[d] 160 hours were required for each spreader tractor complement hauling distances less than 4.8 km (3 mile), and 155 hours for each spreader tractor complement with 2 nurse trucks hauling distance greater than 4.8 km (3 mile).
[f] 182 hours were required for each spreader tractor complement hauling distances less than 4.8 km (3 mile), and 184 hours for each spreader tractor complement with 2 nurse trucks hauling distance greater than 4.8 km (3 mile).
[g] Total annual cost divided by the total field area to which manure was applied.
[h] Average annual cost per lactating cow.

test results allowed soil P build-up, credit was given for all N, P, and K with 100% retention of injected N. Injected manure with soil P build-up was valued at 1.27¢/L (4.8¢/gal; table 15). A broadcast application with next-day incorporation resulted in a 30% loss of the N from volatilization and a 4% loss in nutrient value (table 15; 1.22¢/L; 4.6¢/gal). Unincorporated, broadcast manure lost 90% of the N resulting in a 15% loss in nutrient value. In each case the nutrient value of the manure exceeded the costs for agitation, pumping, land application and injection or broadcast with tillage incorporation.

Manure application at the rate of crop P removal was allowed when the Bray-1 P soil test was between 75 and 150 ppm. When soil test P was at this 'maintenance' level and manure slurry was injected to conserve N, the nutrient value was 0.70¢/L (2.65¢/gal) and the net return over costs was 1.37¢/gal. Allowing soil P to accumulate and reach the 'maintenance' level reduced the credited nutrient value of the manure by 45%. When manure was broadcast at crop P removal rates with a one-day delay in incorporation there was a 50% reduction in credited nutrient value, and the value of unincorporated manure declined by 60% compared to injected slurry with a 'build-up' soil test P.

The net return above costs for agitation, pumping, transport, land application and tillage incorporation ranged from 1.27¢/L (4.8¢/gal) with injection and a 'build-up' soil test P to 0.51¢/L (1.94¢/gal) with unincorporated manure and soil test P in the 'maintenance' range. If manure was applied with a soil test indicating the need to 'draw-down' soil P, no value was given for the manure nutrients and the farm had a negative net return over agitation and hauling costs.

Model Validation

The ownership and operating costs calculated with 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 hauling 22.7 million L (6 million gal) of manure per year and the other was a crop producer hauling 11.4 million L (3 million gal) per year from a nearby dairy. Each livestock manager had current records of costs and labor requirements for their manure hauling operations.

The swine producer raised 9600 finishing pigs to 136 kg (300 lb) each year. The volume of manure hauled in 2008,

Table 14. Fertilizer recommendations, manure nutrients applied, and nutrient credit values for injection application.

	N	P_2O_5	K_2O
	kg/ha (lb/acre)		
Fertilizer recommendation[a]			
Corn grain	131 (117)	54 (48)	39 (35)
Corn silage	158 (141)	56 (50)	154 (120)
Manure nutrients			
Manure nutrients applied	162 (145)	122 (109)	196 (175)
Manure nutrients available[b]	105 (94)	122 (109)	196 (175)
Manure nutrient credits[c]			
Build-up P			
Corn grain	105 (94)	122 (109)	196 (175)
Corn silage	105 (94)	122 (109)	196 (175)
Maintenance P			
Corn grain	105 (94)	54 (48)	39 (35)
Corn silage	105 (94)	56 (50)	154 (120)
Draw-down P			
Corn grain	0 (0)	0 (0)	0 (0)
Corn silage	0 (0)	0 (0)	0 (0)

[a] Based on crop removal, soil test results and manure nutrient analysis (table 6).
[b] Manure N available after losses were calculated as [((Total N - NH_4-N)*mineralization factor) + NH_4-$N_{Retained}$] where Total N = 2.88 kg/1000 L (24 lb/1000 gal), NH_4-N = 1.44 kg/1,000 L (12 lb/1000 gal), mineralization factor = 0.3, and NH_4-$N_{Retained}$ = 100% for injection, see table 15 (Jacobs et al., 1995a,b)
[c] Refer to table 3.

(22,839,670 L, 6,034,259 gal) was within 1% of that calculated with MANURE$HAUL (23,740,125 L, 6,272,160 gal) based on published values for manure production (MWPS, 2004). The swine manure was stored at two locations with an average hauling distance of 1.6 km (1 mile) from each storage pit. Manure was transported and applied with a 205 pto-kW (275 pto-hp) tractor with a 37900-L (10000 gal) tank and injected with a 6-point injector. The farm fuel price in 2008 was $0.85/L ($3.20/gal).

Some of the economic parameters and methods for estimating machinery costs used by the farm managers varied from the default values used in MANURE$HAUL (table 16). Compared to the cost for agitation, pumping, transport, and land application calculated with MANURE$HAUL (0.29¢/L, 1.12¢/gal), the swine producer's calculated cost was 0.32¢/L (1.23¢/gal). When the default and calculated values for depreciation, repair and maintenance, labor wage rate, and pumping and 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.

The cash crop farmer had an agreement with a neighboring dairy 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-hp) tractor and 26,500 L (7000 gal) tractor-drawn spreader for broadcast application with tillage incorporation. The average hauling distance was 4.8 km (3 mile). Costs for tillage incorporation were allocated to the cropping program and were not included in the calculation of hourly costs for manure application. Farm fuel costs in 2008 were $0.86/L ($3.25/gal). Labor was valued at $20/h (table 16). When the labor and fuel costs reported by the crop producer were used in MANURE$HAUL, the calculated hauling cost was $156/h. The crop farmer's reported hourly cost for transport and broadcast application was $155/h.

Conclusions

MANURE$HAUL provided an accurate estimate of on-farm costs and labor requirements for liquid manure agitation, pumping, transport, and land application with top-loading tank spreaders. Predicted equipment ownership

Table 15. Nutrient value of manure for injection, broadcast with incorporation, and broadcast application as a function of soil test results.

		Soil P Level		
		Build-up	Maintenance	Draw-down[b]
Application Method	NH_4-N Retention[a] (%)	¢/L (¢/gal)		
Injection	100	1.27 (4.8)	0.70 (2.65)	0.0 (0.0)
Broadcast w/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)

[a] Jacobs et al. (1995a), Warncke et al., (2004).
[b] Manure application was not allowed when soil test P levels exceeded 150 ppm and P draw-down was required.

Table 16. Economic parameters used in MANURE$HAUL for swine and cash crop producer.

Economic Parameters	MANURE$HAUL	Swine Farm	Cash Crop Farm
Tractor/spreader R&M	Accumulated use	15% of purchase price/yr	Accumulated use
Depreciation period	10 yr	5 yr	10 yr
Labor	$12/h	$15/h	$20/h
Agitate & pump	Pump time plus 16 h/y set-up	$17/h of hauling time	--
MANURE$HAUL cost estimate			
Default values	--	0.29 ¢/L (1.12 ¢/gal)	$147/h
Farm-specific values	--	0.31 ¢/L (1.20 ¢/gal)	$156/h
Farm manager cost estimate		0.32 ¢/L (1.23 ¢/gal)	$155/h

and operating costs were within 1% of the on-farm costs reported by two experienced manure managers.

Equipment ownership and operating costs for liquid manure agitation, pumping, transport, land application, and tillage incorporation ranged from 0.31¢/L (1.18¢/gal) for a 175-cow dairy using a 11,400 L (3000 gal) spreader hauling 1.6 km (1 mile) with broadcast application and tillage incorporation to 0.50¢/L (1.91¢/gal) for a 1400-cow farm with slurry injection and a 6.4-km (4-mile) average haul with two 34,100-L (9000-gal) spreaders and four nurse trucks.

Transport and land application costs were two-thirds of the cost of pumping, agitation, transport, land application, and tillage incorporation. The remaining one-third was for pumping, agitation, and tillage incorporation. Transport and land application costs alone ranged from 0.21¢/L (0.78¢/gal) for a broadcast application with the 175-cow farm to 0.46¢/L (1.74¢/gal) for slurry injection on the 1400-cow farm.

Two nurse trucks with a tractor-drawn spreader were more cost-effective than two tractor-drawn spreaders alone when the hauling distance exceeded 4.8 km (3 mile); however, on a 1400-cow farm the total cost for manure pumping and land application was 16% greater with four nurse trucks for over-the-road transport to two tractor-drawn spreaders than with four tractor drawn spreaders alone. The nurse truck-based system required an additional 210 labor hours per year.

Subsurface injection reduced the farm-average hauling rate (L/h, gal/h) about 20% on a 1400-cow dairy compared to broadcast with tillage incorporation. The annual labor per cow plus replacements for manure agitation, pumping, transport, and application was 0.6 h/cow-yr with broadcast and incorporation and 0.7 h/cow-yr with injection.

The cost of manure transport and land application on a 1400-cow farm was 24% greater with injection than with broadcast without incorporation, but the total cost for agitation, pumping, transport, and injection (0.39/L, 1.48/gal) was only 10% greater than with broadcast and tillage incorporation (0.35/L, 1.34/gal). When the farm-average hauling distance was increased 60% from 4.2 to 6.4 km (2.5 to 4 miles) the total cost increased 11%.

When soil test values allowed a build-up of soil P, credit was given for all N, P, and K with 100% retention of injected N. Broadcast manure with delayed incorporation lost 90% of volatile N and 15% of the manure nutrient value. When high soil test P restricted manure application to crop P removal the credited nutrient value was reduced by 45%. The credited value of unincorporated manure with soil P constrained at crop removal was reduced by 60% compared to injected slurry with soil P at a build-up level. In each case the value of the manure nutrients applied exceeded the cost of agitation, pumping, transport, land application, and incorporation; however, these results are sensitive to fertilizer prices and labor costs.

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