Optimal Utilization of Animal Waste As a Source of Nutrients in Agricultural Production

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INTRODUCTION

Animal wastes contain all the essential micro and macro-elements required for plant growth. Until the end of the 19th century, agriculture was almost wholly dependent on animal wastes and legumes to maintain crop yields. As supplies of inexpensive commercial fertilizer became plentiful after World War II, interest in the utilization of animal wastes as a source of crop nutrients decreased to the point that they were considered nuisance wastes and a source of pollution. This was particularly true in the developed countries of the world. The energy crisis of the early 1970's and the subsequent rapid increase in the price of commercial fertilizer renewed interest in the fertilizer-nutrient value of animal wastes [51].

Land application of animal wastes improves a number of soil properties including soil tilth, water-holding capacity, oxygen content, and soil fertility [25, 26, 39, 40, 42, & 60]. It may also help reduce soil erosion, improve solar heat absorption and increase water infiltration rates [4 and 50]. Even on sandy soils, animal wastes reduce nutrient leaching and increase crop yields [13, 20 & 56]. Because manure has a high moisture holding capacity and because nitrogen is released slowly over time through the process of mineralization of organic molecules, potential leaching losses from manure is less than that of commercial fertilizer.

Livestock and poultry in the United States (U.S.) produce a large amount of wastes annually. An estimated 160 million tons of dry weight animal manure is produced in the U.S. annually. About 39 percent of this total is produced in confined areas. This is the amount available for spreading on land. The 160 million tons of dry weight manure contain 7 million tons of nitrogen, 1.7 million tons of phosphorus, and 3.8 million tons of potassium. Annual commercial fertilizer use is 9.6 million tons of nitrogen, 2.2 million tons of phosphorus, and 4.4 million tons of potassium. In the U.S. only 800,000 tons of nitrogen, 580,000 tons of phosphorous and 1.1 million tons of potassium were spread on cropland in manure [52]. Animal wastes represent one of the most underutilized fertilizer resources in the U.S.

The major outlet for manure is application to cropland. However, three major physical and biological factors may have restricted the use of manure on cropland. These are: (1) pathogen transmission, (2) impact on crop yields, and (3) the nature and composition of the manure. Pathogens do not present restrictions on amounts of manure used when manure is incorporated into the soil, but can limit the amounts used on pastures when surface applied. Azenido and Stout [2] listed 24 diseases that are potentially transmitted by animal manure, most of which enter the animal by ingestion. This emphasizes the need for incorporation of manure into the soil and the potential problems of spreading manure on pastures. Burge [8] concluded that incorporation of manure into the soil by plowing is a sound practice and its application to land represents little threat to the health of humans or animals.

Accumulation of mineral elements that decrease the general physical and chemical quality of the soil as a medium for plant growth can also limit the total amount of manure added to agricultural land [33]. Application of large quantities of manure may cause high salt levels that reduce crop yield. In areas with heavy rainfall and natural leaching, salinity is not a problem. However, in irrigated and low-rainfall areas, application of materials containing salt must be limited [5, 6, 31, 32, 46, 49]. Since most irrigation water contains soluble salts, there are two sources of salt when animal wastes are applied to irrigated land [18]. Corn is a crop with low tolerance to salinity. The application of up to 60 tons of dry weight manure increased corn yield. However, corn yields decreased with the application of greater than 60 tons per acre [51]. Other studies show that the application of 22 tons per acre of manure annually provides adequate nutrients for good crop growth without any deleterious effect on the soil [24, 55]. Yield reductions at high manure application rates have been reported for corn silage by Murphy *et al* [28] and Mathers and Stewart [22]; for grain sorghum by Mathers and Stewart [21]; for corn grain by Liebhardt [19] and Shortall [41]; for Kentucky-31 tall fescue by Jackson *et al* [17].

The greatest problem in the use of animal manure is the direct effects of its nature and composition. Manure is bulky and low-grade fertilizer [10]. Total plant nutrient contents are usually only 10 to 20 percent of those of most commercial chemical fertilizers. Concentrations of nutrients, soluble salts, and trace elements vary greatly and are seldom known. The cost to haul and spread the bulky manure may limit the total amount of manure that can be added to land to satisfy the nutrient requirements of the crops.

Effective utilization of animal wastes as a source of fertilizer for crops is a function of the nutrient requirements of the crops, nutrient content in the manure, mineralization rate of organic molecules in the manure, and costs associated with the hauling and spreading of manure. The mineralization process of organic molecules depends on the soil chemical and physical properties, properties of the organic waste, soil temperature, and the population of microorganisms in the soil. The objective of this study is to evaluate the simultaneous effect of these variables on the optimal quantity of manure that satisfies the nutrient requirements for crops in different rotation systems at least cost.

MINERALIZATION OF ORGANIC MOLECULES

Nitrogen, phosphorus, potassium and sulfur the elements that are most frequently needed by crops in relatively large quantities. Nitrogen, phosphorus, and sulfur are available in the manure in organic form. The availability of these three elements in organic materials has been a subject of study by agronomists for many decades. Data reported by Pratt and Page [35] from a 4-year field trial of bovine manure showed a large variation in contents of nitrogen, phosphorus and potassium. Powers *et al* [30], in a review of data for composition of manure in the U.S., found large ranges in concentration of each of these elements.

Organically combined molecules must be mineralized before the nutrient elements become available to plants [3, 9, 15, and 47]. All previous studies show that phosphorous in manure is equally available to plants as inorganic sources [2, 14, and 38]. Potassium is not part of any organic structure and considered to be equally available to plants as inorganic sources [34, 48]. The main concern for the use of manure as a fertilizer is with nitrogen.

Organic nitrogen in manure must be mineralized before it is available to plants. Thus, the rate of manure application to satisfy the nutrient requirements of plants is determined by the composition of the manure and the nitrogen mineralization rates [30]. Pratt [34] showed that manure added at rates sufficient to supply all or substantial parts of the nitrogen needs of crops will also supply quantities of phosphorus, potassium, and secondary (S, Co, Mg) and minor elements at levels more than adequate for most soil-crop-climate conditions. The mineralization of organic nitrogen in the waste material is dependent on the chemical and physical properties of the waste material as well as those of the soils receiving the waste material [12, 27, and 43].

Gilbertson *et al* [16] showed that the annual mineralization rate of organic nitrogen in animal wastes is positively correlated with the waste's nitrogen content. Pratt [34], based on data from a 4-year field trial, estimated five series of decay constants for manure with different nitrogen contents (Table 1). Willrich *et al* [57] estimated four series of decay constants for manure with different nitrogen contents (Table 2). The results of both studies indicate strong association between the nitrogen content in the manure and the mineralization rate of organic nitrogen.

Table 1: Ratios of yearly mineralization rates to annual application rates of organic materials at constant annual inputs of nitrogen for six decay series for various times following the initial application. [a]

Decay Series	Manure	N content Percent[b]	Time in years							
			1	2	3	4	5	10	15	20
0.90,0.10,0.05	Chicken manure,	4.5	0.90	0.91	0.92	0.92	0.92	0.94	0.95	0.96
0.75, 0.15, 0.10, 0.05	Fresh bovine waste,	3.5	0.75	0.79	0.81	0.82	0.83	0.87	0.90	0.92
0.40, 0.25, 0.06	Dry corral manure,	2.5	0.40	0.55	0.58	0.60	0.63	0.73	0.80	0.85
0.35, 0.15, 0.10, 0.05	Dry corral manure,	1.5	0.35	0.45	0.50	0.53	0.55	0.65	0.73	0.79
0.20, 0.10, 0.05	Dry corral manure,	1.0	0.20	0.28	0.32	0.35	0.38	0.52	0.63	0.72

Source: Pratt [34]

[a]This ratio equals the kg of mineralized nitrogen in any year per kg of nitrogen added per year.

[b]The nitrogen content is on a dry weight basis.

Table 2: Decay constants used to estimate animal-manure nitrogen availability to crops, considering the entire cropping year for degradation of the manure.

Manure Source	N in manure (dry weight basis) percent	Decay constants in years after application			
		1	2	3	4
Poultry (broilers, turkeys)	3.8	.75	.05	.05	.05
Swine	2.8	.90	.04	.02	.02
Dairy, fresh	3.5	.50	.15	.05	.05
Dairy, anaerobic	2.0	.30	.08	.07	.05

Source: Willrich *et al.* [57]

The series of decay constants of .90, .10, and .05 estimated by Pratt [34] for chicken manure with 4.5 percent nitrogen content indicates that 90 percent of the organic N in the manure mineralizes and becomes available to the plant the first year. Ten percent of the residual N becomes available the second year, and 5 percent of the residual N becomes available in the third year, and each following year. The same interpretation may be made for the other series of decay constants shown in tables 1 and 2. The Pratt [34] results also show that the higher the percentage of organic nitrogen in the manure, the higher the percentage of it mineralized within a 20-year period.

Chae and Tabatabai [12] measured the mineralization rate of organic nitrogen over 26-week periods for three types of manure with different chemical properties applied to five types of soil with different physical and chemical properties. The experiments were conducted at 30° C temperature. Proven [37] measured the mineralization rates of organic nitrogen at 20°C and 30°C and showed that soil temperature has a significant effect on the mineralization process.

DATA

Data on the mineralization process of organic nitrogen in unamended and animal manure-treated soils were obtained from Chae and Tabatabai [12]. The data includes three different manure types applied to five different soils. The chemical properties of the three animal manure types studied are shown in table 3. Chicken manure had the lowest C/N ratio followed by cow manure and hog manure. All three manure types

Table 3: Properties of organic waste materials studied

Animal waste material	pH	Organic C	Nitrogen as Total	Nitrogen as NH_4^+	Nitrogen as NO_3^-	C/N Ratio
		g kg^{-1}	gkg^{-1}	mg kg^{-1}		
Chicken	7.7	380	22.0	785	1450	19.22
Hog	6.2	434	21.2	1160	194	21.86
Cow	5.9	473	22.4	204	153	21.45

Source: Chai and Tabatabai [12]

however, have a C/N ratio close to 20. The chemical and physical properties of the five different soils are shown in table 4. The C/N ratios in the soils range from 10.28 to 13.06. The five soils are significantly different in their chemical and physical properties.

The decay of organic waste in soil is accompanied by conversion of carbon (C) and nitrogen (N) into microbial tissue. During this process, part of the C is liberated as CO_2. As the C/N ratio is lowered, and as microbial tissues are attacked (with synthesis of new biomass), a portion of the immobilized organic N is released through net mineralization. The N content of organic residues, as reflected by the C/N ratio, is of primary importance in regulating the magnitude of the two opposing processes of mineralization and immobilization. Residues that have C/N ratios greater than 30, equivalent to N contents of about 1.5 percent or less, result in the lowering of mineral N reserves because of net immobilization by microorganisms. Conversely, residues with C/N ratios of 20 or below, or N contents greater than about 2 percent, lead to an increase in mineral N level through net mineralization [45, pp 164-165]. In this study, both the manure and the soils have C/N ratios lower or very close to 20 and far below 30.

The percentage of organic nitrogen in the manure that mineralized during the 26 weeks incubation period differs significantly by the type of soil that receives the manure. Soil type 1 has the lowest percentage of organic nitrogen mineralized and soil type 5 has the highest percentage of organic nitrogen mineralized (Table 5).

Data on the amount of nitrogen mineralized within successive two-week incubation periods in unamended and manure-treated soils is shown in table 6. The amount of mineralized nitrogen corresponding to each type of manure applied to five

Table 4: Chemical and physical properties of soils used

Soil			Carbon as		Nitrogen as						
Type	Family	pH	Organic	Inorganic	Total	NH_4	NO_3	C/N Ratio	Clay	Sand	Moisture
			$g\ kg^{-1}$		$g kg^{-1}$	$mg\ kg^{-1}$			$g\ kg^{-1}$		
1	Fine-silty, mixed, mesic Mollic Hapludalfs	5.1	18.6	0	1.82	6	6	10.28	190	30	230
2	Fine-loamy, mesic Typic Haplaquolls	6.5	30.8	0	2.51	3	6	12.32	250	380	210
3	Fine-loamy, mesic Typic Calciaquolls	7.6	35.9	29.6	2.76	5	7	13.06	290	330	280
4	Fine-loamy, mesic Mollic Hapludalfs	6.4	12.6	0	1.15	2	5	11.02	170	190	140
5	Fine, montmorillonitic, mesic Cumulic Haplaquolls	7.0	57.6	5.7	4.59	6	10	12.60	400	130	360

Source: Chai and Tabatabai, [12]

Table 5: Percentage of organic N mineralized from organic waste materials added to the soil

Animal Wastes	Percentage of organic N mineralized in soil specified[a]				
	Soil Type 1	Soil Type 2	Soil Type 3	Soil Type 4	Soil Type 5
Chicken	21	54	61	60	67
Hog	16	37	49	42	52
Cow	13	44	36	31	51

Source: Chai and Tabatabai [12]

[a]

$$\left(\frac{\begin{array}{c} Total \quad N \quad \min eralized \quad in \quad waste-treated \quad soil \\ \min use \quad total \quad N \quad \min eralized \quad in \quad waste-treated \quad soil \end{array}}{organic\ N\ added\ in\ waste\ material} \right) \cdot 100$$

different soils includes the amount of mineralized nitrogen released from the soil and the nitrogen released from the mineralization of organic nitrogen in the manure. Cumulative amounts of nitrogen mineralized within successive incubation periods in unamended soils and in manure added to the different soils were generated from the data in table 6. These cumulative amounts of nitrogen were used as the dependent variable in this study and are shown in table 7.

Daily soil temperature in several locations in Idaho is collected each year and compiled for several years by the Idaho Climate Lab. Average daily soil temperature over each two-week period in the year is shown in table 8. Data on hauling and spreading cost was obtained from Custom Hauling and Spreading Service in the Twin Falls area of Idaho in 1997-98. Custom services generally use trucks with 10-ton capacity equipped with 8-foot spreader. They charge $19 per truck for loading and hauling one mile round trip. They also charge $1.50 per mile per truckload for each additional mile after the first mile round trip. For the purpose of this study, custom service charge is used to account for the fixed and variable costs associated with loading, hauling and spreading of manure.

Data on the quantity of recommended commercial fertilizer presently applied to crops in each rotation system considered in this study were obtained from the Crop and Livestock Costs and Returns Estimates, published annually by the Department of Agricultural Economics at the University of Idaho.

Table 6: Amounts of N mineralized within successive incubation periods in unamended and manure-treated soils. N mineralized within successive incubation periods (weeks) specified.

		Incubation Interval													
Soil Type	Animal Manure	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-26	Total
		mg kg^{-1} soil													
1	None	8.6	9.2	15.0	9.2	6.5	6.7	5.1	6.2	8.7	8.7	7.9	8.4	9.3	110
	Chicken	1.7	20.0	33.6	22.8	18.8	18.5	13.9	12.7	11.9	11.3	12.2	11.8	13.2	202
	Hog	0.5	17.5	24.4	20.7	13.6	16.4	15.2	15.3	14.6	10.9	12.5	10.5	11.2	183
	Cow	0.5	13.6	17.2	17.6	14.7	18.1	19.3	17.2	15.4	11.1	10.4	10.5	10.8	176
2	None	10.8	28.2	22.0	36.5	37.4	37.7	27.4	25.7	22.5	20.5	21.5	22.9	23.9	337
	Chicken	7.4	111.0	117.0	76.0	51.3	40.4	32.3	28.2	22.9	21.9	22.8	21.1	25.3	578
	Hog	2.0	64.3	75.1	81.1	55.0	46.0	32.5	26.8	26.2	21.9	22.8	21.5	25.9	501
	Cow	2.6	87.5	94.0	78.8	63.0	38.8	37.0	35.4	23.4	21.4	23.4	21.1	27.1	554
3	None	3.0	5.7	17.4	16.1	11.5	10.4	8.0	7.5	6.1	6.0	5.6	5.5	5.5	108
	Chicken	1.7	36.3	94.5	52.9	42.6	29.6	24.8	20.4	18.0	15.1	16.5	13.5	11.8	378
	Hog	0.0	19.2	66.4	46.3	43.0	30.2	23.2	18.3	17.2	15.9	16.0	15.7	14.4	326
	Cow	0.1	2.5	39.9	44.0	39.5	31.6	27.4	20.9	21.3	17.8	15.7	13.6	12.5	287
4	None	4.7	9.2	9.5	9.4	10.1	10.5	6.8	8.5	5.9	5.0	3.7	4.5	3.3	91
	Chicken	4.2	19.1	66.3	56.3	47.9	35.4	24.0	22.9	49.1	16.7	17.6	14.6	13.4	358
	Hog	0.8	0.8	25.5	42.2	40.4	33.9	30.4	24.4	19.9	16.6	16.0	14.9	12.2	278
	Cow	0.2	0.6	9.4	27.2	37.1	36.6	30.9	23.8	19.8	16.1	14.8	14.8	11.9	243
5	None	11.9	29.5	42.8	40.6	35.9	27.8	20.9	20.8	17.8	17.7	17.1	16.2	17.8	317
	Chicken	12.0	122.0	112.0	86.5	60.8	44.1	36.4	31.8	25.9	24.8	20.8	19.7	21.0	617
	Hog	2.0	75.7	102.0	76.0	58.5	46.5	36.3	36.0	29.4	31.7	29.9	25.5	25.3	574
	Cow	1.1	76.3	104.0	88.9	57.2	51.2	36.3	35.3	29.5	25.9	22.6	20.1	22.3	570

Source: Chai and Tabatabai, [12]

Table 7: Cumulative amounts of nitrogen mineralized within successive incubation periods in unamended soils and in manure.

		Incubation Interval												
Soil Type	Animal Manure	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-26
		mg/Kg^{-1} soil												
1	None	8.6	17.8	32.8	42.2	48.5	55.2	60.3	66.5	75.2	83.9	91.8	100.2	109.5
	Chicken	-6.9	3.9	22.5	36.1	48.4	60.2	36.0	75.5	78.7	81.3	85.6	89.0	92.9
	Hog	-8.1	0.2	9.6	21.1	28.2	37.9	48.0	57.1	63.0	65.2	69.8	71.9	73.8
	Cow	-8.1	-3.7	-1.5	6.9	15.1	26.5	40.7	51.7	58.4	60.8	63.3	65.4	66.9
2	None	10.8	39.0	61.0	97.5	134.9	172.6	200.0	225.7	248.2	268.7	290.2	313.1	337.0
	Chicken	-3.4	79.4	174.4	213.9	227.8	230.5	235.4	237.9	238.3	239.7	241.0	239.2	240.6
	Hog	-8.8	27.3	80.4	125.0	142.6	150.9	156.0	157.1	160.8	162.2	163.5	162.1	164.1
	Cow	-8.2	51.1	123.1	165.4	191.0	192.1	201.7	211.4	212.3	213.2	215.1	213.3	216.5
3	None	3.0	8.7	26.1	42.2	53.7	64.1	72.1	79.6	85.7	91.7	97.3	102.8	108.3
	Chicken	-1.3	29.3	106.4	143.2	174.3	193.5	210.3	223.2	235.1	244.2	255.1	263.1	269.4
	Hog	-3.0	10.5	59.5	89.7	121.2	141.0	156.2	167.0	178.1	188.0	198.4	208.6	217.5
	Cow	-2.9	-6.1	16.4	44.3	72.3	93.5	112.9	126.3	141.5	153.3	163.4	171.5	178.5
4	None	4.7	13.9	23.4	32.8	42.9	53.4	60.2	68.7	74.6	79.6	83.3	87.8	91.1
	Chicken	-0.5	9.4	66.2	113.1	150.9	175.8	193.0	207.4	220.6	232.3	246.2	256.3	266.4
	Hog	-3.9	-12.3	3.7	36.5	66.8	90.2	113.8	129.7	143.7	155.3	167.6	178.0	186.9
	Cow	-4.5	-13.1	-13.2	4.6	31.6	57.7	81.8	97.1	111.0	122.1	133.2	143.5	152.1
5	None	11.9	41.4	84.2	124.8	160.7	188.5	209.4	230.2	248.0	265.7	282.8	299.0	316.8
	Chicken	0.1	92.6	161.8	207.7	232.6	248.9	264.4	275.4	283.5	290.6	294.3	297.8	301.0
	Hog	-9.9	36.3	95.5	130.9	153.5	172.2	187.6	202.8	214.4	228.4	241.2	250.5	258.0
	Cow	-10.8	36.0	97.2	145.5	166.8	190.2	205.6	220.1	231.8	240.0	245.5	249.4	253.9

Table 8: Average daily soil temperature over each two-week period in 1997

Two-Week Period	Two Week Average	Two Week Average
	C°	F°
1	1.15	34
2	3.33	38
3	4.25	40
4	3.53	38
5	2.50	37
6	8.97	48
7	6.98	45
8	9.92	50
9	14.48	58
10	14.07	57
11	15.10	59
12	17.46	63
13	18.97	66
14	24.33	76
15	25.42	78
16	24.19	76
17	22.30	72
18	22.44	72
19	19.50	67
20	14.52	58
21	11.69	53
22	8.23	47
23	5.20	41
24	4.98	41
25	2.26	36
26	-2.26	28

Source: Idaho climate lab, University of Idaho, Moscow, Idaho

METHODS

The mineralization of organic nitrogen is affected by the properties of the manure and the properties of the soil that receives it. Analysis of covariance (ANCOVA) was used to analyze the effect of the fifteen different soil-manure combinations on the mineralization of organic nitrogen.

Analysis of Covariance

The results of the ANCOVA help determine if the entire data set can be analyzed in one model. If the mineralization process is significantly different among the different soil-manure combinations then separate models will be devised to study each combination.

A full model containing dummy variables to separate the effect of each soil-manure combination on the mineralization process over time is shown in Equation 1.

$$Y = b_0 + b_1 \cdot T + \sum_{i=2}^{15} b_{1i} \cdot S_i \cdot T \qquad (1)$$

Where:

Y = the cumulative mineralized nitrogen

b_0 = intercept

b_1 = slope; reflecting the behavior of the mineralization process of the first soil-manure combination over time.

i = is from 2 to 15 (fifteen different soil-manure combinations)

T = time

b_{1I} = slope; reflecting the behavior of the mineralization process due to the i^{th} soil-manure combination

S_I = a dummy variable used to separate the effect of different soil-manure combination

The reduced model generated from Equation 1 is shown in Equation 2.

$$Y = b_0 + b_1 \cdot T \tag{2}$$

The sum of squared error (SSE), for the full and the reduced models were estimated and used to determine the Cow-F statistic as shown in Equation 3.

$$\text{Chow-F} = \frac{\{(SSE_R - SSE_F)/k\}}{\{SSE_F/(n-p)\}} \tag{3}$$

Where:

SSE_R = sum of the squared error for the reduced model

SSE_F = sum of the squared error for the full model

n = number of available observations (195)

p = number of parameters to be estimated by the full model (16)

k = number of parameters omitted from the full model to produce the reduced model.

The Chow-F statistic tests the significance of the reduction in the sum of squared error from the reduced model to the full model. The significance in the error reduction indicates that at least one soil-manure combination is significantly different from the others in its mineralization of organic nitrogen over time.

The Chow-F statistic of 120.37 is significant and indicates that at least one of the soil-manure combinations differ significantly from the others in its mineralization of organic nitrogen over time (Table 9). To determine if more than one soil-manure combination differs in the mineralization of organic nitrogen, the effects of soil and manure were tested separately.

Effect of Soil

The full model used to test the effect of the five different soils on the mineralization of organic nitrogen in the three types of manure is shown in Equation 4.

$$Y = b_0 + b_1 \cdot T + \sum_{i=2}^{5} b_{1i} \cdot S_i \cdot T \qquad (4)$$

Where:

- Y = the cumulative mineralized nitrogen
- b_o = intercept
- b_I = slope; reflecting the behavior of the mineralization process in the first soil over time.
- i = is from 2 to 5 (five different soils)
- T = time
- b_{1i} = slope; reflecting the behavior of the mineralization process due to the i^{th} soil over time
- S_i = a dummy variable used to separate the different soil effects

The reduced model equation is the same as Equation 2.

The Chow-F statistic is 99.34 for chicken manure, 169.83 for hog manure, and 175.78 for cow manure and all are significant (Table 10). The results indicate that at least one of the soils is significantly different in its effect on the mineralization of organic nitrogen when combined with chicken manure, hog manure or cow manure.

Table 9: Sum of the squared errors and Chow-F statistic for fifteen different soil-manure combinations

Statistics	Full Model	Reduced Model
SSE	303,198	2,950,572
d.f.[a]	179	193
R^2	0.95	0.47
Chow-F		120.37
$F_{0.05}$		1.747

[a] degree of freedom for the full model is n-p
degree of freedom for the reduced model is k

Table 10: Sum of the Squared error and Chow-F Statistics for three types of manure applied to five different soils.

	Manure Type		
Statistic	**Chicken**	**Hog**	**Cow**
SSE_F	137,342	64,039	87,079
$d.f._F^a$	59	59	59
R_F^2	0.93	0.96	0.95
SSE_R	1,003,612	754,583	1,058,933
$d.f._R^b$	63	63	63
R_R^2	0.49	0.53	0.44
Chow-F	99.34	169.84	175.78
$F_{0.05}$	2.528	2.528	2.528

[a] $d.f._F = n-p$
[b] $d.f._R = k$

Effect of Manure

The full model used to test the effect of the three different manure applied to five different soils on the mineralization of organic nitrogen is shown in Equation 5.

$$Y = b_0 + b_1 \cdot T + \sum_{i=2}^{3} b_{1i} \cdot S_i \cdot T \qquad (5)$$

Where:

Y = the cumulative mineralized nitrogen

b_o = intercept

b_1 = slope; reflecting the behavior of the mineralization process in the first soil over time

i = is from 2 to 3 (three different manure)

T = time

b_{1i} = slope; reflecting the behavior of the mineralization process due to the i^{th} soil over time

S_i = a dummy variable used to separate the different soil effects

The Chow-F statistics of 21.25, 22.86 and 55.44 are significant for soil type 1, soil type 3 and soil type 4, respectively (Table 11). These statistics indicate that at least one of the manure types differ significantly from the others in its effect on the mineralization of organic nitrogen in soil types 1, 2, 3, 4 and 5.

Table 11: Sum of the Squared error and Chow-F statistics for five different soils receiving three different manure.

Statistic	Soil Type				
	1	**2**	**3**	**4**	**5**
SSE_F	2,759	93,074	34,696	20,907	105,837
$d.f_F^a$	35	35	35	35	35
R_F^2	0.98	0.91	0.93	0.95	0.92
SSE_R	5,929	124,444	77,572	83,562	128,028
$d.f_R^b$	37	37	37	37	37
R_R^2	0.96	0.88	0.84	0.82	0.90
Chow-F	21.25	6.24	22.86	55.44	3.88
$F_{0.05}$	3.267	3.267	3.267	3.267	3.267

[a]$d.f_F$ = n-p
[b]$d.f_R$ = k

Mineralization Models

The results of the ANCOVA clearly indicate that different soil-manure combinations affect the mineralization process of organic nitrogen differently. The chemical and physical properties of both manure and soil are important in the mineralization process of organic nitrogen. Thus, a single statistical model cannot adequately analyze the mineralization of organic nitrogen for all soil-manure combinations.

The mineralization process of organic nitrogen in the soils is essential to determine the quantity of manure required to satisfy the nutrient requirements for crops in a given rotation system. Several linear models were developed and tested for each soil-manure combination. Time is used to model the linear component of the data and logarithm t to cater for the nonlinear part. The results indicate that the primary limitation of the linear models is that these models are not capable of accurately predicting the cumulative mineralized nitrogen after the 26-week incubation period. The results of the linear models show the manure to immobilize in some cases and in other cases the mineralization continues linearly. The results are not consistent with the mineralization of organic nitrogen in unamended and manure-treated soils as shown by the data set.

Four different non-linear functional forms were developed and tested to explain the mineralization process of organic nitrogen. They are; (1) two parameter exponential function, (2) three parameter exponential function, (3) three parameter Weibull function, and (4) four parameter Weibull function. The best-fit nonlinear models are the four-parameter Weibull and the three- parameter exponential. The first assumes time dependent mineralization rates and the second assumes fixed mineralization rate. These models, however, predict that the accumulated mineralized nitrogen reaches an asymptote very fast which sets a limit on the mineralization of organic nitrogen beyond the 26-week incubation period. Consequently, the non-linear models tend to underestimate the actual amount of nitrogen that will mineralize from organic nitrogen in the manure over time.

Exponential smoothing techniques provide an efficient method to reduce volatile short-term fluctuations in time series data. Smoothing methods use last period error to add to or subtract from the current period's reading to predict next period's value. Thus, where there is no trend or seasonal reaction, the simple smoothing approach will follow the movement of the data set about a certain average horizontal line by using last period's error.

Three different exponential smoothing models were compared and tested to select the one that best explains the mineralization process of organic nitrogen in each situation. The three exponential smoothing models are: (1) Double (Brown), (2) Linear (Holt) and (3) Damped Trend. The damped Trend is also referred to as Holt-Winter two-parameter. Mean squared errors and R^2 coefficients calculated for the three exponential models were used as the criteria to select the best model that explains the data set. The results show that the Holt-Winter two-parameter is the best model to explain the mineralization of organic nitrogen. This is due to the dampening component in the data set. In this case the model is divided into three separate components. One for the movement around the mean (level), one for the linear relation (trend), and one for the damped part.

The Holt-winter two-parameter double exponential smoothing with a damped trend is composed of three different equations: one for the level and damping, one for the trend, and one for prediction as outlined below. If the observed accumulated mineralized nitrogen is Y_T in time period T, then:

1. We obtain an updated estimate $a_0(T)$ of the permanent component (level) by using Equation 6.

$$a_0(T) = \alpha \cdot Y_T + (1-\alpha)\cdot \{a_0(T-1) + \phi \cdot b_1(T-1)\} \tag{6}$$

2. We obtain an updated estimate $b_1(T)$ of the trend component (slope) by using Equation 7.

$$b_1(T) = \beta \cdot \{a_0(T) - a_0(T-1)\} + \{(1-\beta)\cdot \phi \cdot b_1(T-1)\} \tag{7}$$

3. A point forecast of the future value $y_{T+\tau}$ made at time T is estimated by Equation 8.

$$\hat{Y}_{T+\tau} = \begin{Bmatrix} a_0(T) + \phi \cdot b_1(T) & 1 \le T \le 13 \,\&\, \tau = 1 \\ a_0(T) + \sum_{i=1}^{\tau} \phi^i \cdot b_1(T) & T \ge 13 \end{Bmatrix} \tag{8}$$

Where:

α = smoothing constant between 0 and 1

ϕ = damping factor between 0 and 1

β = smoothing constant between 0 and 1

$a_0(T)$ = the level component of the cumulative mineralized nitrogen, i.e. the fixed amount or the constant in the predication equation for period T.

$b_1(T)$ = the trend component or the component of the cumulative mineralized nitrogen that changes with time at that period (T). Simply it is the slope component.

$Y_{T+\tau}$ = the T + τ period estimate of the cumulative mineralized nitrogen

T = the last time period in the actual data set after which we are trying to forecast. The maximum number of periods that we have data for is 13 two-week periods for each soil.

τ = extra time after the last period, period 13, that we are trying to forecast for.

We use an iterative procedure introduced by the Forecasting module in the Statistical Analysis System (SAS 6.12), to estimate the initial values, $a_0(0)$ and $b_1(0)$, for the model. The iterative procedure is also used to estimate the values for α, β, and ϕ: These values are changed until the best-fit model is realized and they vary between 0 and 1.

Manure Application Model

The manure application rate per acre is determined by Equation 9.

$$R = \left(P - \sum_{k=0}^{z} \mathrm{Re}\, m_{m+(k\cdot 19)} \right) \Big/ Y_m^a \qquad (9)$$

Where:

R = manure application rate per acre

P = amount of nitrogen required to provide for the plant uptake

Z = number of periods elapsed after the first year up to, but not including, the current year

$\mathrm{Rem}_{m+(m.19)}$ = the cumulative mineralized nitrogen produced from the remaining organic nitrogen applied in year k and available at the last period when the plant uptakes all of its needs of nitrogen in the current year

Y_m^a = cumulative mineralization rate (lbN/lb Manure) adjusted for soil temperature

m = the last period at which the plant uptakes all of its needs of nitrogen in a year. This period varies depending on the crop. and

The maximum number of periods, two-week periods, in a year in which mineralization occurs is 19. Y_m^a is expressed as:

$$Y_m^a = \sum_{j=1}^{m} \left(Y_j - Y_{j-1}\right) \cdot Q_{10j} \cdot \frac{1}{2.24 \cdot 10^4} \tag{10}$$

Where:

j = T+τ

T and τ = as defined in Equation 8

$\hat{Y}_j = \hat{Y}_{T+\tau}$ = defined in Equation (8)

$2.24 \cdot 10^4$ = a constant computed based on Chae and Tabatabai [12]. This constant is equal to $\frac{0.448(kgManure)}{20(kgSoil)} \cdot 1000000$, and is used to transform the units of the cumulative mineralization rate from (mg N/kg Soil) to (lb N/lb Manure).

Q_{10} = temperature effect for any time period j. It depends on the temperature at that period of time.

A typical chemical or enzymatic reaction has an approximate Q_{10} of 2.0. A nonlinear extrapolation method is used to determine the mineralization rate estimated by the best-fit model at different temperatures. The extrapolation relation was shown by Provin [37] to be 2^H if soil temperature (H) is greater than 30°C. $\left(\frac{1}{2}\right)^H$ if less than 30^0C, and zero if soil temperature is less than 5°C.

Cost Model

The hauling and spreading cost to apply manure to crops is a function of the distance traveled, transportation cost per ton/mile after the first mile round trip and the cost per ton for loading and hauling one mile round trip. The hauling and spreading cost is defined in Equation 11.

$$C = \sum_{i=1}^{N} \left(C_L + C_t \cdot (D_i - 1)\right) \tag{11}$$

Where:

C = hauling and spreading cost

C_L = cost of loading and hauling truck load of 10 ton manure for the first mile round trip

C_t = transportation cost for spreading a truck load of 10 ton manure after the first mile round trip

D_i = distance traveled to spread the i^{th} truck load of manure

N = number of truck loads needed to satisfy the nutrient requirements of the crops in a certain size field

The distance traveled to haul and spread the manure (D_i) is the most important variable affecting the cost of utilizing animal waste on cropland. In this study, two field shapes were considered to estimate the distance traveled, they are: (1) rectangular field and (2) circular field.

Rectangular Field

The distance traveled to haul and spread manure on a rectangular field is estimated by Equation 12

$$D_i = \left\{ 2L + \frac{W \cdot 8.25}{R \cdot M} + ([K_{i-1}] + [K_i] - 2) \cdot \frac{M}{5280} + d_{i-1} + d_i \right\} \quad (12)$$

Where:

D_i = the distance traveled to haul and spread the ith load of manure;

i = 1 to N

N = Number of truck loads needed to haul and spread the manure required for a field of size A and is equal to $\frac{R \cdot A}{W}$

R = manure application rate (ton/acre)

A = Area of the field (80 acres), and A is equal to $width \cdot l$

l = Length of the field (0.25 mile)

L = Distance of manure pile from the field in miles (0.5 miles)

$K_i = \frac{i \cdot W \cdot 8.25}{R \cdot M \cdot l}$ = the number of times the truck will go up and down the field to spread the ith load. And $[K_i]\left(\frac{M}{5280}\right)$ is the distance from the edge of the field to the new spreading location for the i^{th} load.

$[K_i]$= a step function equal to the least integer greater than or equal to

K_i

$d_i \; = \left([K_i] + K_i\right) \cdot l$, if ($K_i$) is even

$d_i \; = \left([K_i] + K_i + 1\right) \cdot l$, if ($K_i$) is odd

di = distance traveled from the side of the field to the location of spreading the i^{th} load.

W = capacity of truck in tons (10 tons)

M = width of spreader (8 ft)

Circular field

The distance traveled to haul and spread manure on a circular field is estimated by Equation 13.

$$D_i = \left\{ 2L + \frac{W \cdot 8.25}{R \cdot M} + K_{i-1} + K_i + d_{i-1} + d_i \right\} \qquad (13)$$

Where:

Di, L, W, R, and M as defined in Equation 12

i = 1 to Q

$K_i \; = \dfrac{i \cdot W \cdot 8.25}{R \cdot M} - \sum_{j=i}^{O_1} \pi \cdot (r - j \cdot M)$, if O_i is even

$K_i \; = \{\pi \cdot (r - j \cdot M)\} - \left(\dfrac{i \cdot W \cdot 8.25}{R \cdot M} - \sum_{j=i}^{O_1} \pi \cdot (r - j \cdot M) \right)$ if O_i is odd

$d_i \; = \left((O_1 - 1) \cdot \dfrac{M}{5280} \right)$

O_i = The number of times the truck will go up and down the field when spreading the i^{th} load

r = the radius of the field in miles

In the case of the circular field the cost function is shown in Equation 14.

$$C = 2 \cdot \sum_{i=1}^{Q} C_L + C \cdot (D_i - 1) \qquad (14)$$

Where:

$Q = \frac{N}{2}$, and Q is calculated using File Maker Pro software.

Maximum distance

The maximum distance traveled to equate the cost of applying the required quantity of manure to the cost of commercial fertilizer to satisfy the nutrient requirements of crops in a given rotation system is estimated by Equations 15 and 16

$$L_{mas} = \frac{(C_S - C)}{2N \cdot C_t} \cdot A, \qquad \text{for a rectangular field.} \qquad (15)$$

$$L_{max} = \frac{(C_S - C)}{4Q \cdot C_t} \cdot A, \qquad \text{for a circular field.} \qquad (16)$$

Where:

L_{max} = the maximum distance traveled

C_s = the cost of commercial fertilizer, and C,N,A,Q and C^tas defined in Equations 12 and 13.

RESULTS

The Damped Trend exponential smoothing is the best model to estimate the cumulated mineralized nitrogen from organic nitrogen over time. A summary of the

Damped Trend statistics for all soil-manure combinations is shown in table 12. The coefficients are highly significant for all combinations. Figures 1 to 5 show the trend in cumulative mineralized nitrogen over time as estimated by Damped Trend model. Figures 3, 4, and 5 show that the mineralization of organic nitrogen is faster and at a higher rate for manure applied to soil type 3, soil type 4, and soil type 5 compared to soil type 1 and soil type 2. The results also indicate a higher percentage of organic nitrogen in manure, applied to soil type 3, soil type 4, and soil type 5 mineralized compared to manure, applied to soil type 1 and soil type 2.

Manure Application Rate

Manure application rates per acre were determined for crops in the two rotation systems considered in this study, these are: (1)Potato-Wheat-Wheat (PWW) and (2) Sugerbeets-Wheat-Wheat (SWW). For rotation system 1, the quantities of manure that satisfy the nutrient requirements for the crops stabilize at the seventh year of the rotation and thereafter (Table 13). For the three crops in this rotation planted in soil type 1, the quantities of manure stabilize at 72-0-20 tons for chicken manure, 87-8-22 ton for hog manure, and 97-23-30 tons for cow manure. The quantity of manure to satisfy the nutrient requirements for the crops planted in soil type 1 is significantly higher than the four other soil types. Soil type 1, compared to the other four types of soil, has significantly lower pH and significantly less percentage of sand content.

The quantities of manure that satisfy the nutrient requirements of the same crops planted in soil type 4, are the lowest. For soil type 4, the quantities of manure stabilize at

Table 12: Summary for the best fit exponential smoothing models

Soil Type	Manure Type	Model	Coefficients		Weight			R^2	MSE
			$a_0(T)$	$b_1(T)$	Level	Trend	Damping		
1	Control	Damped Trend	109.50	8.57	0.999	0.482	0.982	0.9940	5.74
	Chicken		92.78	3.91	0.767	0.999	0.945	0.9930	7.55
	Hog		73.83	2.04	0.963	0.732	0.949	0.9940	4.65
	Cow		66.90	1.50	0.999	0.999	0.917	0.9900	8.00
2	Control	Damped Trend	337.00	23.66	0.999	0.860	0.981	0.9970	27.98
	Chicken		240.60	1.39	0.999	0.999	0.879	0.9500	263.16
	Hog		164.10	1.99	0.999	0.999	0.893	0.9720	85.01
	Cow		216.50	3.19	0.999	0.999	0.890	0.9700	139.80
3	Control	Damped Trend	108.30	5.51	0.999	0.414	0.965	0.9900	11.98
	Chicken		270.28	6.96	0.615	0.999	0.923	0.9720	192.14
	Hog		27.64	9.65	0.630	0.999	0.938	0.9810	94.91
	Cow		178.50	7.00	0.999	0.999	0.897	0.9860	58.43
4	Control	Damped Trend	91.20	3.54	0.777	0.999	0.962	0.9980	1.58
	Chicken		266.40	10.73	0.999	0.401	0.949	0.9720	181.65
	Hog		186.90	8.90	0.999	0.999	0.890	0.9850	73.42
	Cow		152.10	8.60	0.999	0.999	0.918	0.9880	42.40
5	Control	Damped Trend	316.80	17.80	0.999	0.999	0.965	0.9970	24.21
	Chicken		301.00	3.20	0.999	0.999	0.902	0.9880	90.33
	Hog		258.00	7.54	0.999	0.964	0.917	0.9900	64.25
	Cow		253.90	4.50	0.999	0.999	0.913	0.9880	81.49

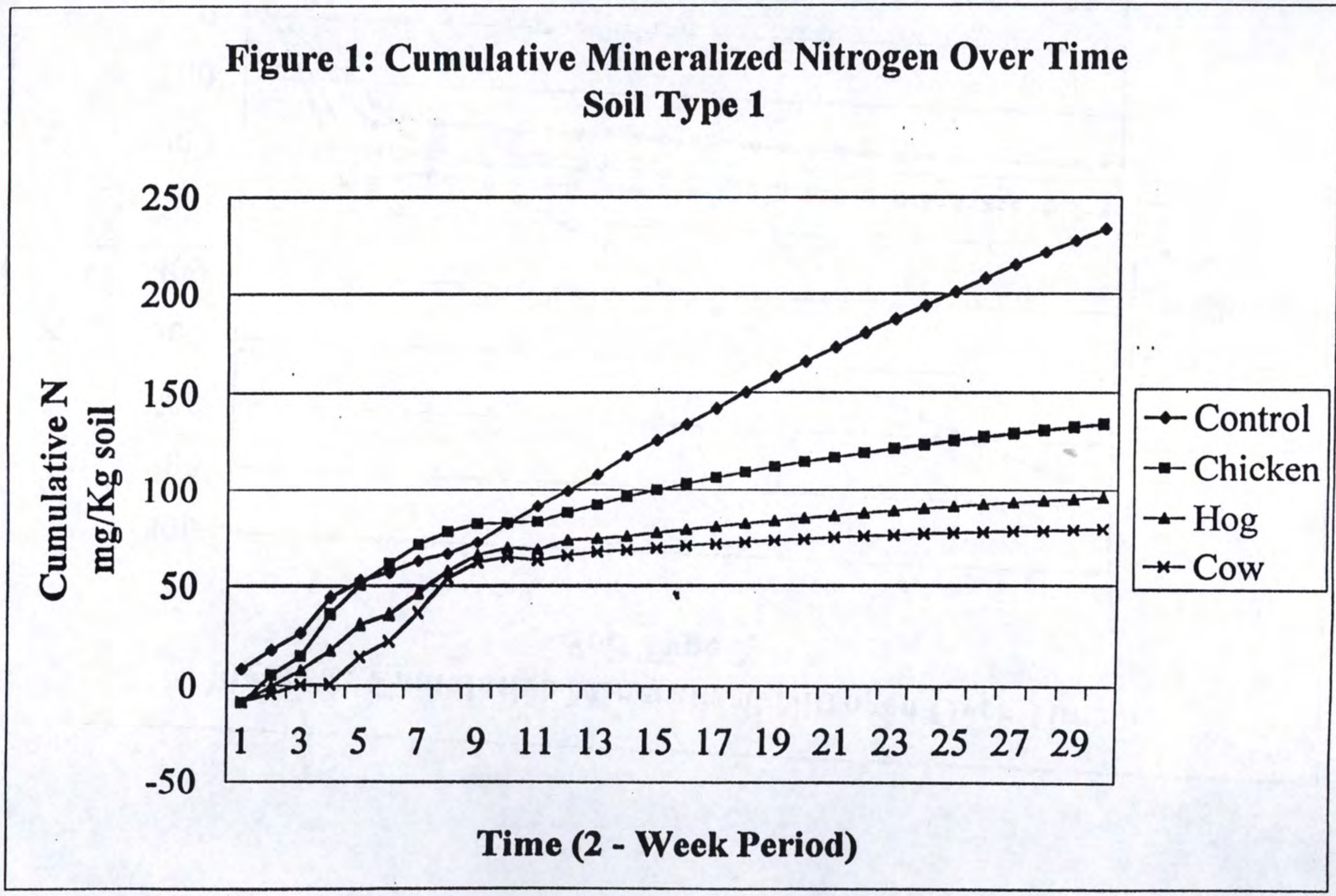
Figure 1: Cumulative Mineralized Nitrogen Over Time
Soil Type 1
Cumulative N
mg/Kg soil
250
200
150
100
50
0
-50
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29
Time (2 - Week Period)
Control
Chicken
Hog
Cow

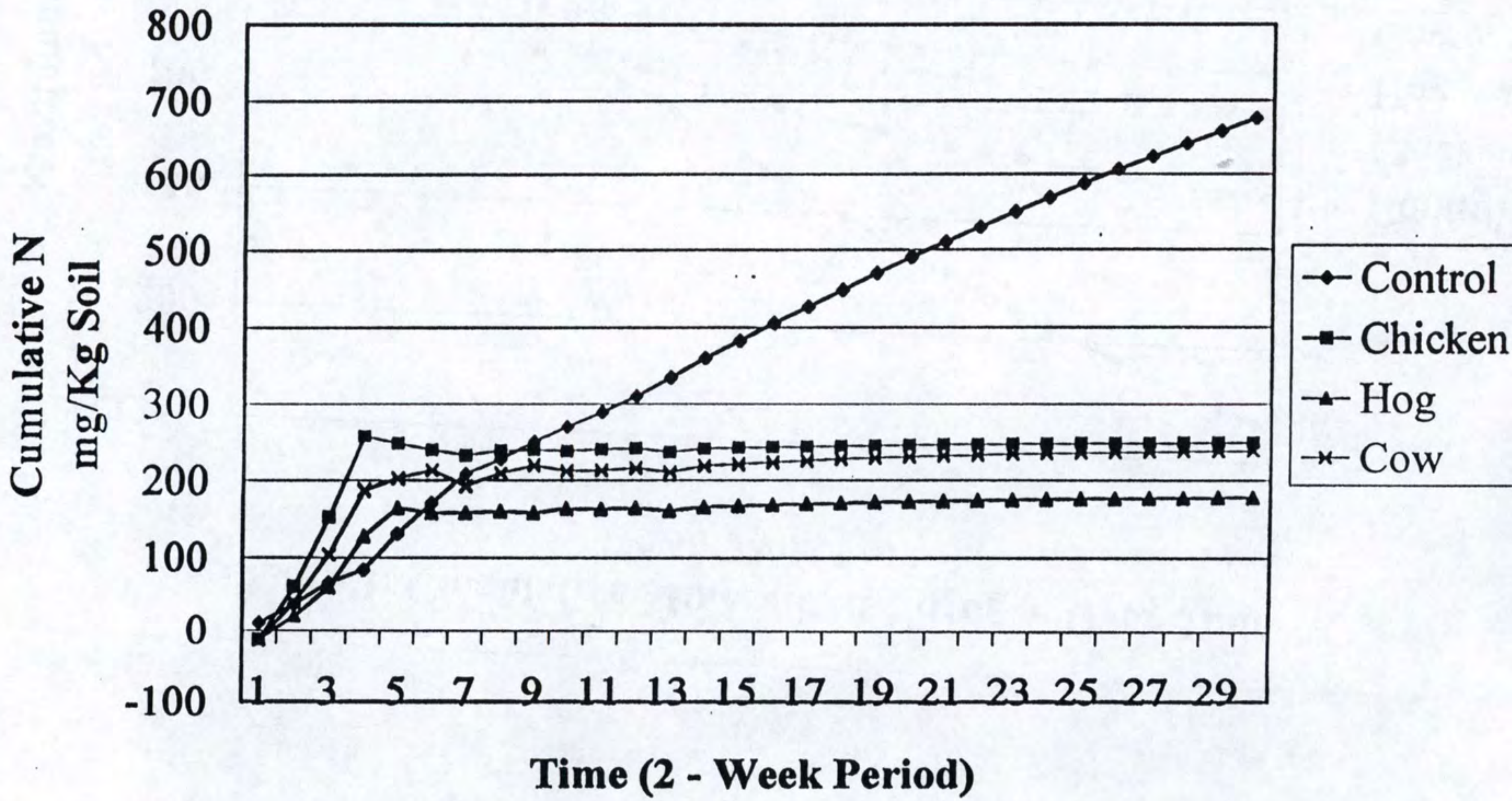

Figure 2: Cumulative Mineralized Nitrogen Over Time
Soil Type 2

Figure 3: Cumulative Mineralized Nitrogen Over Time
Soil Type 3

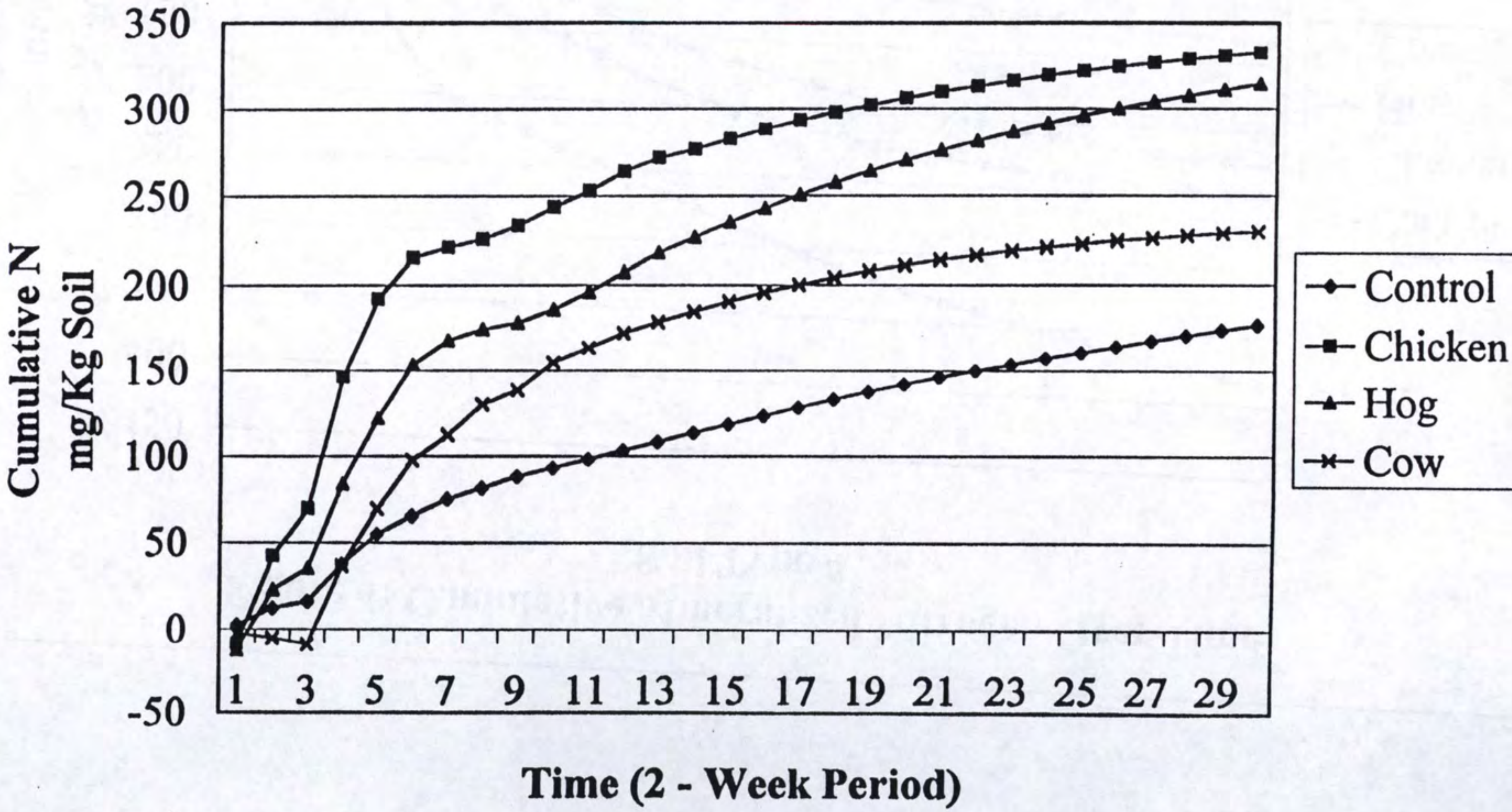

Figure 4: Cumulative Mineralized Nitrogen Over Time
Soil Type 4

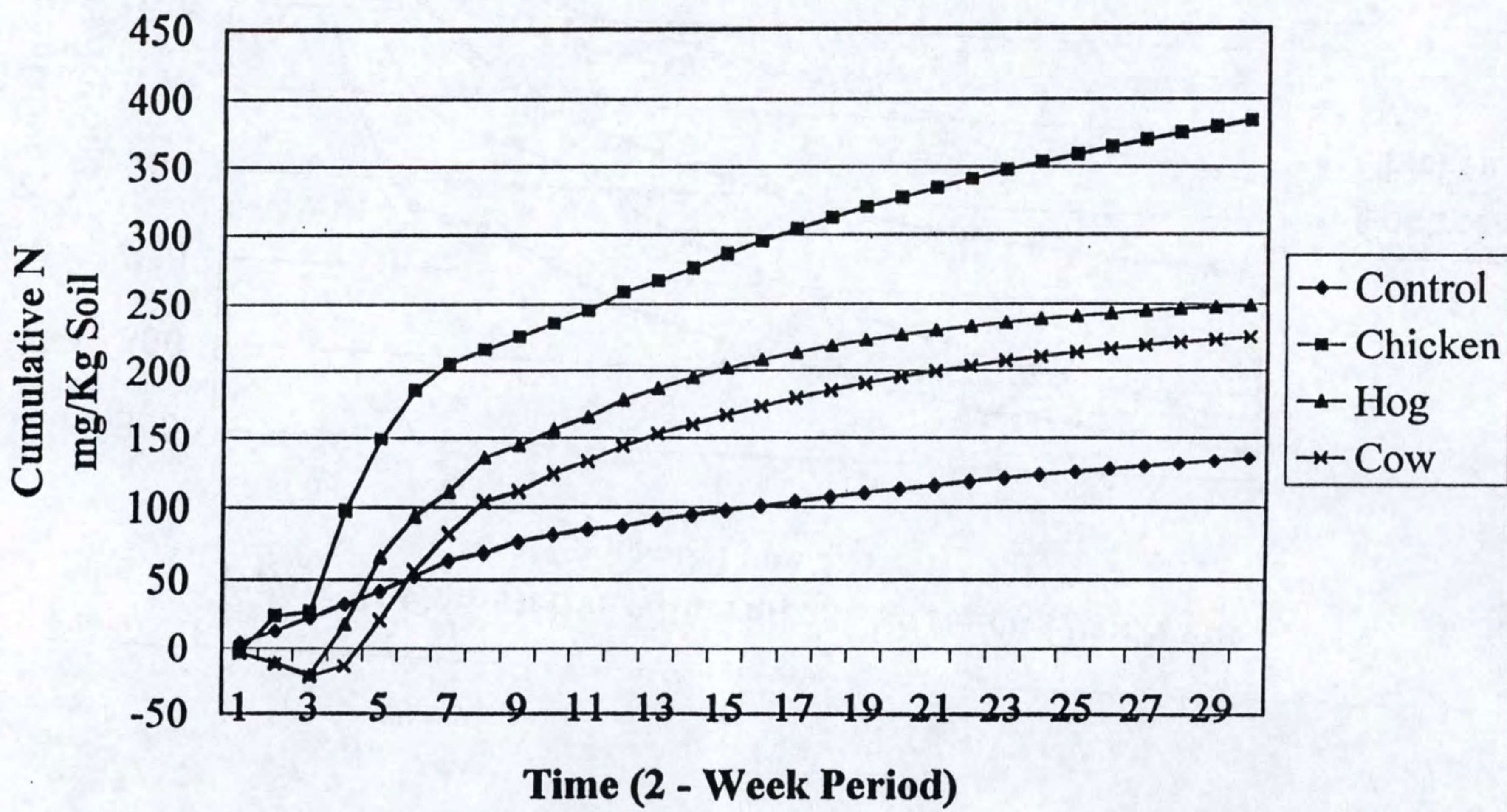

Figure 5: Cumulative Mineralized Nitrogen Over Time
Soil Type 5

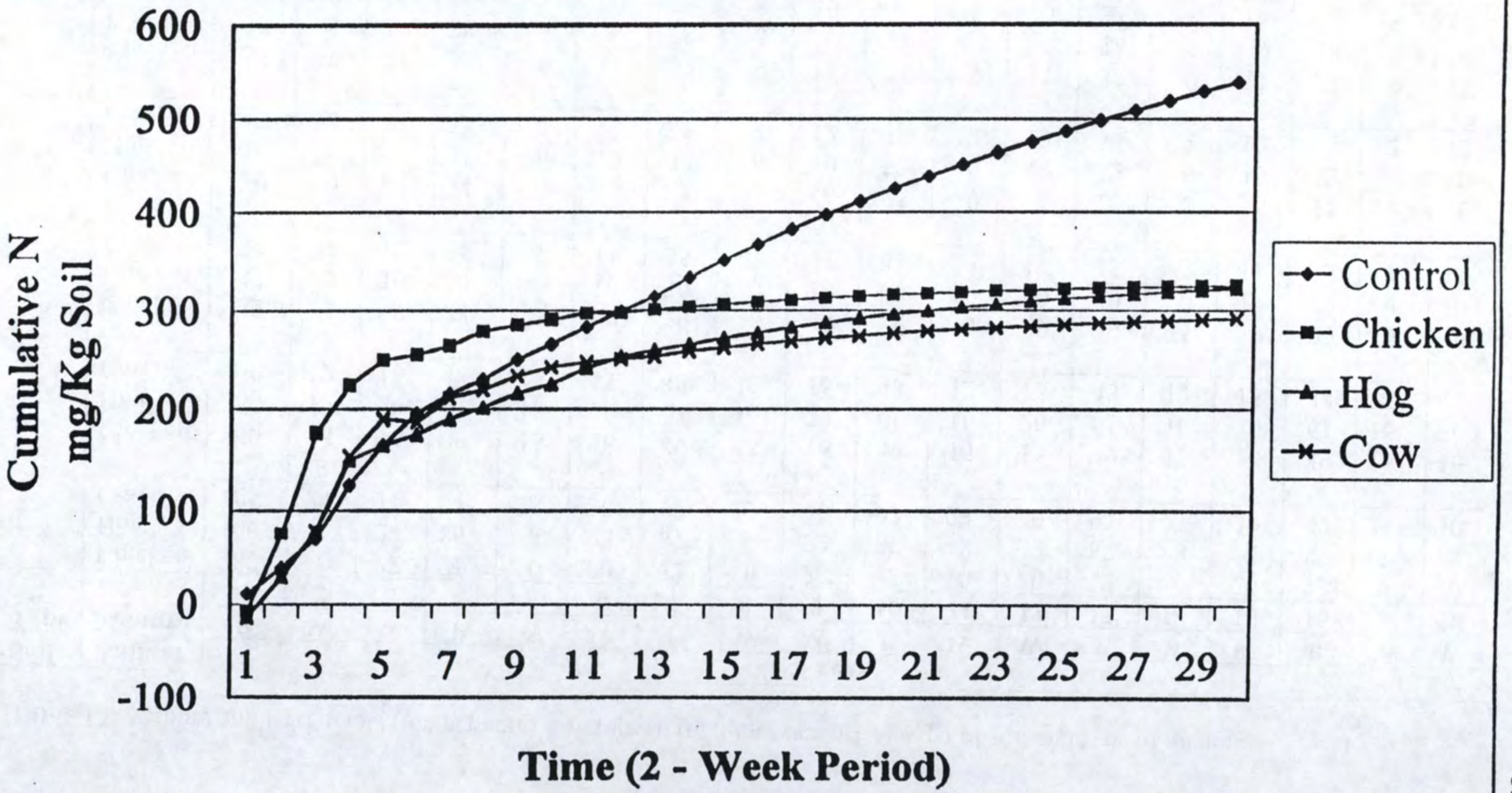

Table 13: Manure application rate (ton per acre) for crops in rotation system 1 by type of soil and type of manure

Soil Type	Animal Manure	Year																	
		P	W	W	P	W	W	P	W	W	P	W	W	P	W	W	P	W	W
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Chicken	87	0	22	71	0	20	72	0	20	72	0	20	72	0	20	72	0	20
	Hog	100	11	24	86	8	22	87	8	22	87	8	22	87	8	22	87	8	22
	Cow	105	24	31	97	23	30	97	23	30	97	23	30	97	23	30	97	23	30
2	Chicken	50	15	16	49	15	16	49	15	16	49	15	16	49	15	16	49	15	16
	Hog	64	17	20	61	16	20	61	16	20	61	16	20	61	16	20	61	16	20
	Cow	50	12	16	48	12	15	48	12	15	48	12	15	48	12	15	48	12	15
3	Chicken	32	5	9	28	5	9	29	5	9	29	5	9	29	5	9	29	5	9
	Hog	37	0	10	30	0	10	30	0	10	30	0	10	30	0	19	30	0	10
	Cow	39	7	12	35	7	11	35	7	11	35	7	11	35	7	11	35	7	11
4	Chicken	29	0	7	24	0	6	25	0	6	25	0	6	25	0	6	25	0	6
	Hog	36	6	11	31	6	10	32	6	10	32	6	10	32	6	10	32	6	10
	Cow	42	2	13	35	2	12	35	2	12	35	2	12	35	2	12	35	2	12
5	Chicken	35	9	11	33	9	11	33	9	11	33	9	11	33	9	11	33	9	11
	Hog	32	5	9	28	5	9	28	5	9	28	5	9	28	5	9	28	5	9
	Cow	35	8	10	33	8	10	33	8	10	33	8	10	33	8	10	33	8	10

25-0-6 tons for chicken manure, 32-6-10 tons for hog manure, and 35-2-12 tons for cow manure. For soil type 5, the quantities of manure stabilize at 33-9-11 tons for chicken manure, 28-5-9 tons for hog manure, and 33-8-10 tons for cow manure. Soil type 4 and soil type 5 compared to the other soils, have the highest pH, the highest inorganic carbon content, the highest nitrogen content, the highest clay content, the highest moisture content, and the highest percentage of mineralized organic nitrogen.

For rotation System 2, the quantities of manure that satisfy the nutrients requirement for the crops in the rotation also stabilize at the seventh year of the rotation and thereafter (Table 14). For the three crops in this rotation planted in soil type 1, the quantities of manure stabilize at 30-14-18 tons for chicken manure, 39-21-23 tons for hog manure, and 46-30-30 for cow manure. The quantity of manure to satisfy the nutrient requirements for the crops planted in soil type 1 is significantly higher than the four other soil types. On the other hand soil type 4 required the lowest quantities of manure and stabilized at 10-5-6 tons for chicken manure, 15-10-9 tons for hog manure, and 16-9-10 tons for cow manure.

Manure Application Cost

Manure application cost per acre is a function of the quantity of manure required, distance traveled, and cost per ton-mile to haul and spread the manure. The manure application cost per acre is analyzed for rectangular and circular fields for rotation system 1 and rotation system 2. For both rotations, the cost per acre to apply manure to circular

Table 14: Manure application rate (ton per acre) for crops in rotation system 2 by type of soil and type of manure

Soil Type	Animal Manure	Year																	
		S	W	W	S	W	W	S	W	W	S	W	W	S	W	W	S	W	W
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Chicken	45	15	19	30	14	18	30	14	18	30	14	18	30	14	18	30	14	18
	Hog	51	25	24	38	21	23	39	21	23	39	21	23	39	21	23	39	21	23
	Cow	54	32	31	46	30	30	46	30	30	46	30	30	46	30	30	46	30	30
2	Chicken	26	16	16	25	16	16	25	16	16	25	16	16	25	16	16	25	16	16
	Hog	33	20	20	31	19	20	31	19	20	31	19	20	31	19	20	31	19	20
	Cow	26	15	16	24	15	15	24	15	15	24	15	15	24	15	15	24	15	15
3	Chicken	17	9	9	13	8	8	13	8	8	13	8	8	13	8	8	13	8	8
	Hog	19	7	9	13	7	8	13	7	8	13	7	8	13	7	8	13	7	8
	Cow	20	11	11	16	11	10	16	11	10	16	11	10	16	11	10	16	11	10
4	Chicken	15	5	6	10	5	6	10	5	6	10	5	6	10	5	6	10	5	6
	Hog	19	10	10	14	10	9	15	10	9	15	10	9	15	10	9	15	10	9
	Cow	22	10	11	15	9	10	16	9	10	16	9	10	16	9	10	16	9	10
5	Chicken	18	11	11	16	11	11	16	11	11	16	11	11	16	11	11	16	11	11
	Hog	16	9	9	13	8	8	13	8	8	13	8	8	13	8	8	13	8	8
	Cow	18	10	10	16	10	10	16	10	10	16	10	10	16	10	10	16	10	10

fields is lower than the rectangular field. The reason is that the distance traveled to spread the manure on a circular field is less than that for rectangular fields.

Cost per acre to apply manure to crops in rotation system 1 and rectangular field is the lowest for soil type 4. It ranges from 18 percent of the cost of commercial fertilizer for chicken manure to 28 percent of the cost of commercial fertilizer for each of hog manure and 29 percent of commercial fertilizer cost for cow manures. Soil type 3 is second in manure application cost ranging from 23 percent of the cost of commercial fertilizer for hog manure to 26 percent for chicken manure and 31 percent for cow manure. Manure application costs on soil type 5 is 25 percent of the cost of commercial fertilizer for hog manure, 30 percent for cow manure, and 31 percent for chicken manure. Manure application cost is significantly higher for soil type 1 and soil type 2. Manure application cost is slightly lower for circular field compared to rectangular field for all manure - soil combinations (Table 15).

In general, the cost of manure application on crops in rotation system 1 is lower than the cost of commercial fertilizer for all soil-manure combinations. For rectangular fields, the cost ranges from 86 percent of the cost of commercial fertilizer for cow manure applied to soil type 1 to 18 percent of the cost of commercial fertilizer for chicken manure applied to soil type 4 . For circular fields, the cost ranges from 84 percent for cow manure applied to soil type 1 to 18 percent for chicken manure applied to soil type 4 (Table 15).

Cost per acre to apply manure to crops in rotation system 2 seems to be close for soil type 3, soil type 4, and soil type 5. Cost per acre to apply manure is the lowest for

Table 15: Manure application cost per acre for rectangular and circular fields and one mile distance from the manure source and the field, rotation system 1.

Soil Type	Animal Manure	Rectangular Field							
		Application Cost per Acre ($)				Percent of Commercial Fertilizer[a]			
		P	W	W	Total	P	W	W	Total
1	Chicken	146	0	42	**188**	54	0	93	**52**
	Hog	177	18	46	**241**	66	40	103	**67**
	Cow	197	48	62	**307**	73	107	139	**86**
2	Chicken	100	32	34	**166**	37	71	76	**46**
	Hog	124	34	42	**200**	46	76	93	**56**
	Cow	98	26	34	**158**	36	58	76	**44**
3	Chicken	60	12	20	**92**	22	27	44	**26**
	Hog	62	0	22	**84**	23	0	49	**23**
	Cow	72	16	24	**112**	27	36	53	**31**
4	Chicken	52	0	14	**66**	19	0	31	**18**
	Hog	66	14	22	**102**	25	31	49	**28**
	Cow	72	6	26	**104**	27	13	58	**29**
5	Chicken	68	20	24	**112**	25	44	53	**31**
	Hog	58	12	20	**90**	22	27	44	**25**
	Cow	68	18	22	**108**	25	40	49	**30**

Soil Type	Animal Manure	Circular Field							
		Application Cost per Acre ($)				Percent of Commercial Fertilizer[a]			
		P	W	W	Total	P	W	W	Total
1	Chicken	144	0	41	**185**	54	0	91	**52**
	Hog	174	18	45	**237**	65	40	100	**66**
	Cow	194	47	61	**302**	72	104	136	**84**
2	Chicken	99	31	33	**163**	37	69	73	**45**
	Hog	123	33	41	**197**	46	73	91	**55**
	Cow	97	25	31	**153**	36	56	69	**43**
3	Chicken	59	12	20	**91**	22	27	44	**25**
	Hog	61	0	22	**83**	23	0	49	**23**
	Cow	71	15	23	**109**	26	33	51	**30**
4	Chicken	51	0	13	**64**	19	0	29	**18**
	Hog	65	13	22	**100**	24	29	49	**28**
	Cow	71	6	25	**102**	26	13	56	**28**
5	Chicken	67	20	23	**110**	25	44	51	**31**
	Hog	57	12	20	**89**	21	27	44	**25**
	Cow	67	18	22	**107**	25	40	49	**30**

[a]Commercial fertilizer cost per acre is $269 for potato and $45 for wheat

chicken manure applied to soil type 4. The cost of applying chicken manure to soil type 4 is 28 percent of the cost of commercial fertilizer for rectangular field and 27 percent for circular field. The cost of applying hog manure to soil type 3 is 36 percent of the cost of commercial fertilizer for rectangular field and 35 percent for circular field. For all soil-manure combinations, the cost of manure application on crops in rotation system 2 and rectangular field ranges from a high of 126 percent of the cost of commercial fertilizer for cow manure applied to soil type 1 to a low of 27 percent for chicken manure applied to soil type 4 (Table 16).

Maximum Distance

The economic potential of utilizing manure on cropland as an alternative to commercial fertilizer is influenced by the cost of hauling and spreading the manure. This cost is influenced by the distance between the source of the manure and the field that receives it. The maximum distance to transfer manure to the field, after the initial one mile round trip, that will equate the cost of hauling and spreading manure with the cost of commercial fertilizer is shown in table 17.

For a rectangular field the maximum distance for rotation system 1 range from a low of 1.15 miles for cow manure applied to soil type 1 to a high of 31.55 miles for chicken manure applied to soil type 4. For rotation system 2 it is not economical to apply hog and cow manure to soil type 1. For the other soil types, the maximum distance ranges from a low of 1.22 miles for hog manure applied to soil type 2 to a high of 19.44 miles for chicken manure applied to soil type 4.

Table 16: Manure application cost per acre for rectangular and circular fields and one mile distance from the manure source and the field, rotation system 2.

Soil Type	Animal Manure	Rectangular Field								Circular Field							
		Application Cost per Acre ($)				Percent of Commercial Fertilizer[a]				Application Cost per Acre ($)				Percent of Commercial Fertilizer[a]			
		S	W	W	Total	S	W	W	Total	S	W	W	Total	S	W	W	Total
1	Chicken	62	29	38	**129**	76	64	84	**75**	61	29	37	**127**	74	64	82	**74**
	Hog	80	44	48	**172**	98	98	107	**100**	79	43	47	**169**	96	96	104	**98**
	Cow	94	62	62	**218**	115	138	138	**126**	93	61	61	**215**	113	136	136	**125**
2	Chicken	52	34	34	**120**	63	76	76	**70**	51	33	33	**117**	62	73	73	**68**
	Hog	64	40	42	**146**	78	89	93	**85**	63	39	41	**143**	77	87	91	**83**
	Cow	50	32	32	**114**	61	71	71	**66**	49	31	31	**111**	60	69	69	**65**
3	Chicken	28	18	18	**74**	34	40	40	**37**	28	18	18	**64**	34	40	40	**37**
	Hog	28	16	18	**62**	34	35	40	**36**	28	15	18	**61**	34	33	40	**35**
	Cow	34	24	22	**80**	41	53	49	**47**	33	23	22	**78**	40	51	49	**45**
4	Chicken	22	12	14	**48**	27	27	31	**28**	22	12	13	**47**	27	27	29	**27**
	Hog	32	22	20	**74**	39	49	44	**43**	31	22	20	**73**	38	49	44	**42**
	Cow	34	20	22	**76**	41	44	49	**44**	33	20	22	**75**	40	44	49	**44**
5	Chicken	34	24	24	**82**	41	53	53	**48**	33	23	23	**79**	40	51	51	**46**
	Hog	28	18	18	**74**	34	40	40	**37**	28	18	18	**64**	34	40	40	**37**
	Cow	34	22	22	**78**	41	49	49	**45**	33	22	22	**77**	40	49	49	**45**

[a]Commercial fertilizer cost per acre is $82 for potato and $45 for wheat

Table 17: Maximum distance in miles between the field and the manure source, after the first mile round trip, that equates the cost of manure application with the cost of commercial fertilizer

Soil Type	Animal Manure	Rectangular Field								Circular Field							
		Rotation System 1				Rotation System 2				Rotation System 1				Rotation System 2			
		P	**W**	**W**	**Rotation**	**S**	**W**	**W**	**Rotation**	**P**	**W**	**W**	**Rotation**	**S**	**W**	**W**	**Rotation**
1	Chicken	6	NA	0	**6.14**	2	4	1	**2.21**	6	NA	1	**6.23**	2	4	1	**2.26**
	Hog	4	11	0	**3.35**	0	0	0	**-0.03**	4	11	0	**3.43**	0	.2	0	**0.04**
	Cow	2	0	-2	**1.15**	-1	-2	-2	**-1.48**	3	-.4	-2	**1.23**	-1	-2	-2	**-1.41**
2	Chicken	12	3	2	**8.03**	4	2	2	**3.02**	12	3	2	**8.10**	4	2	2	**3.08**
	Hog	8	2	0	**5.40**	2	1	0	**1.22**	8	2	1	**5.46**	2	1	1	**1.29**
	Cow	12	5	2	**8.91**	5	3	3	**3.60**	12	5	3	**9.07**	5	3	3	**3.67**
3	Chicken	24	23	10	**21.19**	14	11	11	**12.13**	24	22	9	**21.26**	14	11	11	**12.19**
	Hog	23	NA	8	**22.96**	34	15	11	**13.25**	23	NA	8	**23.03**	14	15	11	**13.31**
	Cow	19	14	6	**15.60**	10	7	7	**8.22**	19	14	6	**15.68**	10	7	7	**8.29**
4	Chicken	29	NA	16	**31.55**	19	24	17	**19.44**	29	NA	17	**31.61**	19	24	17	**19.51**
	Hog	21	18	7	**17.82**	11	8	9	**9.65**	21	18	7	**17.89**	11	8	9	**9.71**
	Cow	19	55	5	**17.13**	10	9	9	**9.16**	19	5	5	**17.20**	10	8	8	**9.22**
5	Chicken	20	9	6	**15.45**	10	7	6	**7.88**	20	9	7	**15.52**	10	7	7	**7.96**
	Hog	25	23	10	**21.49**	14	11	11	**12.22**	25	22	10	**21.55**	14	11	14	**12.28**
	Cow	21	12	8	**16.58**	10	8	7	**8.69**	21	12	8	**16.65**	10	8	8	**8.77**

For a circular field, the maximum distance for rotation system 1 ranges from a low of 1.23 miles for cow manure applied to soil type 1 to a high of 31.61 miles for chicken manure applied to soil type 4. For rotation system 2 it is not economical to apply cow manure to soil type 1. For all other soil-manure combinations, the maximum distance ranges from a low 1.29 miles for hog manure applied to soil type 2 to a high of 19.51 miles for chicken manure applied to soil type 4.

SUMMARY

For centuries manure has been used as a source of nutrient elements for plants. In addition to its fertilizing value, manure application improves the physical structure of the soil. In the United States over 160 million tons of animal wastes, 40 percent of which is produced in confined areas, is regarded as a problem to be 'disposed of' rather than a resource to be 'used'. The best alternative for the use of animal wastes is on cropland.

Effective utilization of animal wastes, as a source of fertilizer, however, is a function of the cost associated with hauling and spreading the wastes on cropland. This cost varies with the quantity of manure needed to satisfy the nutrient requirements of the crops in any rotation system. The quantity of manure needed is a function of the nutrient content and the mineralization rate of organically combined elements in the waste. The objective of this study was to evaluate the simultaneous effect of these variables in determining the optimal quantity of manure that satisfies the nutrient requirements for various crops in different rotation systems at least cost.

Nitrogen, phosphorus, and potassium are the elements that are most frequently needed in relatively large quantities. Phosphorus in manure is equally available to plants as inorganic sources. Potassium is not part of any organic structure and considered to be equally available to plants as inorganic sources. The main concern for the use of manure as a fertilizer is with nitrogen. Nitrogen in manure must be mineralized before it is available to plants. This rate of manure application to satisfy the nutrient requirements of plants is determined by the mineralization rate of organic nitrogen. The mineralization of organic nitrogen is a function of the manure properties, properties of the soil that receives the manure, and soil temperature.

Analysis of Covariance (ANCOVA) is used to test the effect of manure properties and soil properties on the mineralization rate of organic nitrogen for fifteen different soil-manure combinations. The Cow-F statistic for all soil-manure combinations was estimated. The results indicate a significant difference in the mineralization of organic nitrogen among the fifteen different soil-manure combinations. Therefore, it is determined that no one statistical model can be used to analyze the entire data.

The mineralization rate of organic nitrogen in the soil is essential to determine the quantity of manure required to satisfy the nutrient requirements of crops in a given rotation system. Several statistical models were developed and applied to analyze the mineralization process of organic nitrogen for each soil-manure combination. Linear, non-linear, and exponential smoothing models were developed and applied. The results show that exponential smoothing models best explained the mineralization process of organic nitrogen. Three exponential smoothing models were developed and applied. They are: (1) Double (Brown), (2) Linear (Holt) and (3) Damped Trend. The R^2 and MSE coefficients calculated for each model indicate that Damped Trend is the best statistical model to explain the mineralization rate of organic nitrogen for each soil-manure combination.

The mineralization rate of organic nitrogen over time was used in a mathematical model to determine the manure application rate per acre for each soil-manure combination. The quantity of manure needed to be hauled and spread on cropland will determine the distance needed to be traveled. The distance traveled determines the manure application cost. This distance is a function of the quantity of manure to be hauled and spread, cost of hauling and spreading per ton/mile, truck capacity, and the width of the spreader. Two mathematical models were developed to estimate the distance traveled and the cost, one for rectangular field and the other for circular field. A statistical model was developed to estimate the maximum distance from the source of the manure to the receiving field that will equate the cost of applying manure with the cost of commercial fertilizer.

The results of this study show that the quantity of manure required to satisfy the nutrient requirements of crops in two rotation systems is significantly affected by the properties of the manure and properties of the soil that receives the manure. The two rotation systems are: (1) potato-wheat-wheat and (2) sugarbeets-wheat-wheat. The quantity of manure required for rotation systems 1 and 2 decreases over time and it stabilizes at the fourth year of the rotation in some cases and at the seventh year of the rotation for most cases. Manure requirement for crops in rotation system 1 planted in soil type 1 stabilizes at 72-0-20 ton per acre for chicken manure, 87-8-22 ton per acre for hog manure, and 97-23-30 ton per acre for cow manure. Manure requirement for crops in rotation 2 planted in soil type 4 stabilizes at 25-0-6 ton per acre for chicken manure, 32-6-10 ton per acre for hog manure, and 35-2-12 ton per acre for cow manure.

Cost per acre to apply manure to crops in rotation system 1 planted in soil type 4 ranges from a low of 18 percent of the cost of commercial fertilizer for chicken manure to a high of 29 percent of commercial fertilizer for cow manure. Soil type 3 and soil type 5 are second and third respectively in manure application cost per acre. For soil type 3 the cost ranges from 23 percent of the cost of commercial fertilizer for hog manure to 26 percent for chicken manure. For soil type 5 the cost ranges from 25 percent of the cost of commercial fertilizer for hog manure to 30 percent of the cost of commercial fertilizer for cow manure.

Manure application cost per acre for crops in rotation system 2 is also lower in soil type 4 compared to the other four types of soil analyzed in this study. It ranges from a low of 36 percent of the cost of commercial fertilizer for hog manure to a high of 47 percent of the cost of commercial fertilizer for cow manure. For all soil-manure combinations the cost of manure application on crops in rotation system 2 ranges from a high of 126 percent of the cost of commercial fertilizer for cow manure applied to soil type 1 to a low of 28 percent of the cost of commercial fertilizer for chicken manure applied to soil type 4.

For rotation system 1, the maximum distance to transfer manure from the source of the manure to the receiving field that will equate the cost of applying manure to the cost of commercial fertilizer ranges from a low of 1.23 miles for cow manure applied to soil type 1 to a high of 31.61 miles for chicken manure applied to soil type 4. For rotation system 2, it is not economical to apply cow manure to soil type 1. For all other soil-manure combinations, the maximum distance ranges from a low 1.29 miles for hog manure applied to soil type 2 to a high of 19.51 miles for chicken manure applied to soil type 4.

In general, animal wastes can be used economically on cropland at significantly lower cost than the cost of commercial fertilizer. However, the properties of the wastes and the properties of the soils that receive the wastes significantly influence the cost of using manure on cropland. The cost of applying manure can be as low as 18 percent of the cost of commercial fertilizer in some cases. In most cases, this cost ranges from 25-40 percent of the cost of commercial fertilizer.

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