Preliminary Estimates of Nitrogen Availability from Liquid Dairy Manure to Potato

Meghan A. Curless and Keith A. Kelling¹

ADDITIONAL INDEX WORDS. *Solanum tuberosum*, fertilizer equivalence, nutrient, soil, petiole

SUMMARY. Within Wisconsin, there is a distinct movement toward dairy herd expansion and consolidation of small farms. These large dairies are considering various land and manure management arrangements with non-livestock farmers, such as potato (*Solanum tuberosum*) producers to increase their manure management options. This study used a fertilizer equivalence approach to evaluate the availability of nitrogen from dairy manure to potatoes. Nitrogen (N) availability was evaluated in field experiments in 2000 and 2001, conducted in northeast Wisconsin using a moderate and a high liquid dairy manure rate [10,000 and 20,000 gal/acre (93,536 and 187,072 L·ha⁻¹)] compared with results obtained from N fertilizer applied at five rates [0 to 240 lb/acre (269.0 kg·ha⁻¹)]. Availability estimates using the fertilizer equivalence method based on tuber yield, harvested tuber N concentration and uptake, petiole nitrate concentration, and soil nitrate levels resulted in apparent availability of manurial N from 10% to 40%, with an overall average across both years of 29.2%. This level is only slightly less than values typically measured where corn has been used as the test crop. In spite of being more shallow-rooted and perhaps somewhat less efficient in N use it does not appear that adjustments to manurial N availability estimates are warranted when potatoes are grown.

Although a substantial amount of research has been done on the impact of manure on succeeding crops, relatively little research has examined its influence on potatoes. Even though manure contains a significant quantity of nutrients, the specific amounts of these nutrients vary depending on animal type and age, composition of feed ration, type and amount of bedding, climatic conditions, storage and handling systems, and method of field application (Azevedo and Stout, 1974; Gilbertson et al., 1979; Smith and Peterson, 1982). Additional uncertainty exists relative to the amount of these nutrients that are available to a succeeding crop. Accurate estimates of availability are essential if manure nutrients are to be effectively recycled in crops.

Manure N is composed of relatively unstable urea in the liquid portion and a relatively stable organic N fraction in the feces and bedding. About 50% of the total N excreted by dairy cows is in the form of urea in the urine (Azevedo and Stout, 1974; Powell and Wu, 1999). In the presence of the urease enzyme, the urea hydrolyzes to ammonium bicarbonate and then converts rapidly to ammonia–ammonium where it may be adsorbed by the clay particles, volatilized, or simply stays as ammonium in the soil water (Bitzer and Sims, 1988).

Department of Soil Science, University of Wisconsin-Madison, 1525 Observatory Drive, Madison, WI 53706-1299.

Support of this research provided by the Wisconsin Potato and Vegetable Growers Association Potato Industry Board, the Wisconsin Fertilizer Research Council, Wisconsin Department of Agriculture, Trade & Consumer Protection ADD grant program, the UW-Madison Graduate School and UW College of Agricultural & Life Sciences is gratefully acknowledged.

¹To whom reprint requests should be addressed; e-mail kkelling@wisc.edu.

The amount of N that is available to the crop is the sum of the contributions from urea and the mineralization of the more stable organic fractions, minus the amount that is lost to leaching or volatilization. Research estimating the N availability from dairy manure has shown that from 10% to 60% is available in the first year after application with an average of 37% available when corn (*Zea mays*) is used as a test crop (Jemison and Fox, 1994; Jokela, 1992; Klausner and Guest, 1981; Magdoff et al., 1984; Motavalli et al., 1989; Pratt et al., 1976). Along with the nutrient value of manure, its addition can have a significant effect on soil properties, such as an improvement of soil cation exchange capacity, organic matter content, bulk density, and water holding capacity (Black and White, 1973).

Potatoes may respond to manure as a nutrient source differently than other crops such as corn since they have a much shallower [<3 ft (0.9 m) versus 5 ft (1.5 m) for corn] and less dense root system (Powelson et al., 1993). Potatoes also put their energy into below-ground growth and produce very large amounts of dry matter (tubers) and are notoriously inefficient users of applied N. Although some scientists have looked at the impact of manure on potato yield and tuber quality (Grandy et al., 2002; Lee and MacDonald, 1977; Sharma et al., 1980), few have actually experimentally determined N availability of manure to this crop.

One approach to estimating nutrient availability is by using fertilizer equivalence. This method attempts to accurately determine the amount of fertilizer nutrient that produces the same yield, nutrient uptake, or other measured response that is found for a given amount of the nutrient from manure. This approach is based on the assumption that the parameters chosen are appropriate measures of nutrient

availability and that nutrients from manure and fertilizer-amended areas are taken up with the same efficiency (Klausner and Guest, 1981; Motavalli et al., 1989). A response is fitted to the experimental values obtained for inorganic fertilizer and the fertilizer equivalence is found by determining the fertilizer rate with an equivalent response, determined by the curve, as that of the manure. The equivalent fertilizer N rate is then divided by the total manure N applied to calculate nutrient availability.

The objective of this preliminary study was to determine the N availability to potatoes from liquid dairy manure for the first 2 years of the work using the fertilizer equivalence method.

Materials and methods

Research plots were established in Fall 1999 at the Langlade County Airport Experiment Station, Antigo, Wis. (lat. $45^{\circ}8'N$, long. $89^{\circ}9'W$) on an Antigo silt loam (fine-silty over sandy or sandy-skeletal, mixed Typic Glossoboralfs) in randomized complete blocks using four replications. Liquid dairy manure from the Purina Dairy in Antigo, Wis. was broadcast in the fall preceding potato planting to 18×50 ft (5.5×15.2 m) strips with a liquid spreader truck at a moderate and high rate and incorporated within 3 d in November 1999, and then on a new plot area in November 2000. The amount of manure applied each year, as well as its dry matter and nutrient content are presented in Table 1.

Results from the manure treatments were compared with those obtained from N fertilizer plots where five rates of N [0, 60, 120, 180, or 240 lb/acre (0, 67.2, 134.5, 201.7, or 269.0 kg·ha⁻¹) were used. Nitrogen fertilizer was applied by hand in a band on the potato row in two applications with one-third at emergence as ammonium sulfate

and two-thirds at mid-tuberization as ammonium nitrate. To ensure adequacy of phosphorus (P), 240 lb/acre (269.0 kg·ha⁻¹) of P₂O₅ was broadcast as triple super phosphate to all plots directly before planting and incorporated by the planter. Potassium was also applied to all plots as a preplant broadcast application of 400 lb/acre (448.3 kg·ha⁻¹) of muriate of potash and incorporated by the planter. Each plot [six rows by 20 ft (6.1 m)] was planted to 'Snowden' potatoes in May 2000 and 2001 with an in-row spacing of 1 ft (30.5 cm) and row widths of 3 ft (91.4 cm) with 550 lb/acre (616.5 kg·ha⁻¹) of 2N-0.9P-9.3K starter fertilizer as a carrier for the systemic insecticide imidacloprid. Other pest management and irrigation practices followed the standard practice for the area and were performed by the station personnel.

Preplant and postharvest soil samples were taken in 2000 and 2001 to a depth of 3 ft in 1-ft increments, by taking four cores down the center of the row and four cores from each side approximately 3 inches (7.6 cm) from the center line for a total of 12 cores per plot. Midseason surface soil samples 0 to 1 ft were collected at about 30 d after emergence (DAE) and again at 60 DAE. Soils were oven dried at about 140 °F (60.0 °C) in a forced air dryer and ground to pass a 12-mesh screen. Nitrate-N was determined according to a modification of the procedure described by Liegel et al. (1980). The potassium chloride extract was filtered through Whatman #2 paper and analyzed colorimetrically using QuickChem Method 13-107-04-1-B (Lachat Instruments, 1992a) on a Lachat autoanalyzer (Lachat Instruments, Milwaukee, Wis.).

An assessment of crop N status was provided by nitrate-N analysis of petioles sampled four times during each growing season (26 to 30, 36 to 44, 44 to 60, and 57 to 75 DAE). Each

Table 1. Application rates and chemical analyses of liquid dairy manure applied to potato experimental plots at Antigo, Wis., Fall 1999 and 2000.

Year	Rate applied (gal/acre) ^z	Dry matter applied (%)	Ammonium nitrogen applied	Total nitrogen applied (lb/acre) ^y	Phosphate applied	Potash
1999						
Low	10,000	9.2	106	328	154	209
High	20,000	9.2	213	655	308	418
2000						
Low	10,853	6.6	178	306	123	249
High	19,349	6.5	295	539	226	455

^z 1 gal/acre = 9.35 L·ha⁻¹.

^y 1 lb/acre = 1.12 kg·ha⁻¹.

Table 2. Effect of fertilizer and manure nitrogen (N) rate on harvested potato tuber yield, tuber total N concentration, and tuber N uptake at Antigo, Wis., 2000–01.

Treatment	N rate (lb/acre) ^z	2000			2001		
		Total yield (cwt/acre) ^y	N conc (%)	N uptake (lb/acre)	Total yield (cwt/acre)	N conc (%)	N uptake (lb/acre)
Control	0	422	1.20	113	329	1.21	90
Fertilizer	60	528	1.44	161	341	1.45	109
	120	566	1.45	171	333	1.22	91
	180	580	1.44	178	321	1.38	99
	240	523	1.78	194	332	1.24	91
	327/306	528	1.38	150	381	1.44	119
Manure ^x	654/539	606	1.51	187	375	1.41	115
P value		0.01	<0.01	<0.01	0.24	0.17	0.19
LSD _{0.05}		87	0.22	33.5	NS	NS	NS

^z1 lb/acre = 1.12 kg·ha⁻¹.

^y1 cwt/acre = 0.112 Mg·ha⁻¹.

^xTotal N in manure in 2000 and 2001.

^{ns}Nonsignificant at $P = 0.05$

sample consisted of 40 petioles per plot taken from the 4th or 5th leaf from the growing point, usually in the afternoon. Petioles were dried at 150 °F (65.6 °C) and ground to pass through a 40-mesh screen. Samples (0.1 g) were extracted with distilled water and nitrate-N analysis was performed colorimetrically using a Lachat autoanalyzer (Lachat Instruments, 1992a).

In late September 2000 and early October 2001, the two center rows of each plot were machine harvested. The tubers were graded into US#1, B [not retained on a 2-inch (5.1-cm) screen], and cull (off shape, blemished, green, diseased). A 30- to 40-lb (13.6- to 18.1-kg) sample of the US#1 tubers were size graded into <6 oz (170 g), 6 to 10 oz (284 g), and >10 oz categories. Tubers were analyzed for total N following a semi-micro Kjeldahl digestion procedure adapted from Liegel et al. (1980). The digestions were performed on 250 mg of tuber tissue in Pyrex Folin-Wu tubes (Corning Glass Works, Corning, N.Y.) graduated at 50 mL. The digests were then diluted to 50 mL, filtered and analyzed for total N colorimetrically on the Lachat autoanalyzer (Lachat Instruments, 1992b), using the QuickChem Method 13-107-06-1-A, with sodium phenate, and 5.2% sodium hypochlorite.

Manure N availability was estimated by the fertilizer equivalence method. For each rate and year, crop responses from the manure treatments were compared with those obtained from inorganic fertilizer treatments. Tuber yield and total N concentration, N uptake, petiole N, and soil N values at all samplings were regressed against the fertilizer N rates to establish the

N response curve for each parameter. Fertilizer equivalence values were calculated by establishing the point on the crop response curve for each manured plot, and then calculating the fertilizer rate that would have produced the same response. Fertilizer equivalents were determined for each replication and averaged.

Statistical analyses was performed using the SAS software (SAS Institute, 1990). Where there were equivalent measures repeated in time, analyses of variance was used. Standard errors were calculated using the SAS software, as the sample standard deviation divided by the number of observations in the sample. Regression analysis by linear, quadratic and exponential models were performed to determine crop response to fertilizer rate.

Results and discussion

Tuber yield, tuber N concentration, and tuber N uptake values from the fertilizer and manure treatments for 2000 and 2001 are presented in Table 2. It is apparent that manure provided some advantage to the growth of the crop beyond just N as the yield and tuber N concentration and uptake values of the high manure rate in 2000 and both rates in 2001 exceeded the values obtained from all other N fertilizer treatments. In 2000, the low manure rate responded the same as the 60-lb/acre rate of N fertilizer. Orthogonal contrast of treatments for 2000 yield found significance between control versus others ($P < 0.01$), control versus fertilizer ($P < 0.01$) and control versus manure ($P < 0.01$). The lack of significant crop response to the addition of fertilizer N in 2001 was likely due to the healthy stand of red clover (*Trifolium pratense*) present the previous season that was not killed and plowed under until the spring

of 2001. The presence of this legume may have provided additional N to the potato crop early in the season. A pairwise contrast performed on the 2001 yield data showed that a contrast of manure versus fertilizer was significant at $P = 0.05$, with manure resulting in greater yield. Data for the other measured parameters (petiole N and soil N) are not given; however, significant fertilizer treatment responses were seen at all sampling times in both years.

Nitrogen availability estimates were made by first fitting regression curves to the experimental data from the fertilizer treatments for the various parameters measured. Regression analysis was performed by testing several models (linear, quadratic, or quadratic-plateau), and the best-fit model as determined by the largest significant R^2 value was used for each parameter (Table 3). The regression equations show significant responses to all parameters in both years except for yield, tuber N concentration and tuber N uptake in 2001.

Estimates of N availability for 2000 and 2001 by the fertilizer equivalence method based on tuber yield, harvested tuber N uptake and concentration, mid-season and harvest soil nitrate levels and petiole nitrate levels are presented in Table 4. In 2000, for the low manure rate an estimate of apparent N availability from the manure of 19.4% was calculated using yield and generally similar results were obtained using tuber N concentration or tuber N uptake. At the high manure rate in 2000 an estimate could not be made using yield because the high manure treatment had a greater yield than all of the fertilizer treatments. This was also true for the 60 DAE petiole sampling and for the 30 DAE soil sampling for both manure rates in 2000. Estimates using the petiole and soil parameters

Table 3. Regression equations fitted to various potato responses (Y) to fertilizer nitrogen (N) rate (X) in 2000 and 2001 used to calculate N availability values from liquid dairy manure using the fertilizer equivalence approach at Antigo, Wis., 2000–01.

Parameter ^a	n ^y	Equation	R ²	P value
2000				
Total yield (cwt/acre) ^x	20	$Y = 424.9 + 1.759 X - 0.054 X^2$	0.507	0.003
Tuber N concentration (%)	20	$Y = 1.234 + 0.17 X$	0.518	0.001
Tuber N uptake (lb/acre) ^x	20	$Y = 118.9 + 0.53 X - 0.001 X^2$	0.648	<0.001
Petiole, 30 DAE ^x (%)	20	$Y = 16.54 + 0.029 X$	0.500	0.002
Petiole, 44 DAE (%)	20	$Y = 4.21 + 0.142 X - 0.0004 X^2$	0.925	<0.001
Petiole, 60 DAE (%)	20	$Y = 0.435 + 0.1 X - 0.00019 X^2$	0.743	<0.001
Petiole, 75 DAE (%)	20	$Y = 0.9 + 0.0317 X$	0.704	<0.001
Soil, 0–1 ft, 30 DAE (ppm) ^x	20	$Y = 27.67 + 0.438 X - 0.001 X^2$	0.525	0.002
Soil, 0–1 ft, 60 DAE (ppm)	20	$Y = 21.98 + 0.222 X$	0.443	0.001
Soil harvest, 0–1 ft (ppm)	20	$Y = 29.41 - 0.004 X + 0.0006 X^2$	0.516	0.001
Soil harvest, 0–3 ft (lb/acre)	20	$Y = 49.62 - 0.018 X + 0.001 X^2$	0.614	<0.001
2001				
Total yield (cwt/acre)	20	$Y = 333.9 - 0.027 X + 0.000018 X^2$	0.002	0.987
Tuber N concentration (%)	20	$Y = 1.25 + 0.002 X - 0.000005 X^2$	0.058	0.321
Tuber N uptake (lb/acre)	20	$Y = 94.12 + 0.112 X - 0.0004 X^2$	0.028	0.524
Petiole, 26 DAE (%)	20	$Y = 1.43 + 0.004 X - 0.00001 X^2$	0.323	0.036
Petiole, 36 DAE (%)	20	$Y = 1.36 + 0.007 X - 0.0014 X^2$	0.714	0.001
Petiole, 44 DAE (%)	20	$Y = 1.19 + 0.01 - 0.00002 X^2$	0.691	0.001
Petiole, 57 DAE (%)	20	$Y = 0.66 + 0.013 X - 0.0027 X^2$	0.865	0.001
Soil, 0–1 ft, 26 DAE (ppm)	20	$Y = 52.2 + 0.71 X - 0.009 X^2$	0.706	0.001
Soil, 0–1 ft, 58 DAE (ppm)	20	$Y = 16.1 + 0.96 X - 0.014 X^2$	0.870	0.001
Soil harvest, 0–1 ft (ppm)	20	$Y = 25.54 + 0.45 X$	0.787	0.001
Soil harvest, 0–3 ft (lb/acre)	20	$Y = 44.4 + 0.78 X$	0.869	0.001

^aPetiole and soil values are nitrate-N.

^yNumber of individual plot observations in the regression.

^x1 cwt/acre = 0.112 Mg·ha⁻¹, 1 lb/acre = 1.12 kg·ha⁻¹, DAE = days after emergence, 1 ft = 30.5 cm, ppm = mg·ha⁻¹.

for 2000 were generally similar to those obtained using the tuber parameters except for the very high values seen for the 30 DAE petioles and the 60 DAE soil samples. Overall for this experiment in 2000, the low manure and the high manure rates resulted in roughly the same availabilities of 30% to 32%.

In 2001, yield and tuber N responses to fertilizer rate were not significant, therefore no availability estimates were calculated using these parameters. However, the rest of the equivalence parameters had relatively high R^2 values and the estimates of availability values were generally similar to those obtained the previous year with the low rate and the high rate, averaging 26.9 and 23.0% availability, respectively.

The petiole nitrate concentrations from both the low and high manure rate show an interesting trend. The percentages of N availability at 30 DAE in 2000 at both rates were very high, (69% for the low rate and 52% for the high rate). For the three subsequent sampling dates, there was a substantial drop in estimated N availability to an average of 24.6% for the low rate, and 25.8% for the high rate, indicating an apparently larger concentration of N from the manure in the petiole earlier in

the season. These results are counter to our expectations since the equivalence is based on the total amount of manure N applied including the organic fraction, which we would expect to be more slowly available. This may be misleading with respect to estimating N availability as illustrated by the lower but consistent percentages of availability for the remaining three samplings. The same general trend held true in 2001.

Comparing these results with others that have performed similar availability experiments on corn show that the dairy manure N may be slightly less available to potato, however, these differences appear minor. Klausner et al. (1994) estimated mineralization constants for dairy and beef manure and found that they usually fall between 16 to 21% for yield and N uptake of corn. Similarly, Jokela (1992) reported N availability of 39% from dairy manure to corn. Other researchers who conducted experiments to determine the availability of liquid dairy manure such as Klausner and Guest (1981), Motavalliet al. (1989), and Jemison and Fox (1994) estimated N availabilities at 42%, 32%, and 54% respectively. Chambers et al. (1999), evaluating poultry manure on potato, found the mean N availability

to be 38% when manure was applied late winter–early spring and 32% from fall–early winter applications.

Although potato may respond differently to the addition of manure due to its relatively shallow rooting system and relatively high N requirements, the N availability estimates from this experiment using fertilizer equivalence are generally similar or only slightly lower than the results reported by others for liquid dairy manure to corn. The exceptionally high yields of the manure treatments indicate that the manure was providing benefits beyond N and P nutrients. Overall we saw an estimate of 29.4% availability of N from about 10,418 gal/acre (97,446 L·ha⁻¹) of manure that provided 317 lb/acre (355.3 kg·ha⁻¹) of N, and 26.7% availability from about 199,675 gal/acre (1,867,679 L·ha⁻¹) of manure containing 598 lb/acre (670.3 kg·ha⁻¹) of N.

Literature cited

- Azevedo, J. and P.R. Stout. 1974. Farm animal manures: An overview of their role in the agricultural environment. Calif. Agr. Expt. Sta. Ext. Serv., Davis, Manual 44.
- Bitzer, C.C. and J.T. Sims. 1988. Estimating the availability of nitrogen in poultry manure through laboratory and field studies. J. Environ. Qual. 17:47–54.

Table 4. Liquid dairy manure nitrogen (N) availability as calculated by the fertilizer equivalence approach, using various potato responses in 2000 and 2001.

Year/ parameter ^z	Low manure rate		High manure rate	
	Fertilizer equivalence (lb/acre) ^y	N availability (%)	Fertilizer equivalence (lb/acre)	N availability (%)
2000 ^x				
Tuber yield	63	19.4	NA ^w	NA
Tuber N concn	75	22.8	147	22.4
Tuber N uptake	60	18.2	193	29.0
Petiole, 30 DAE ^y	226	68.8	343	52.1
Petiole, 44 DAE	81	24.7	123	19.0
Petiole, 60 DAE	89	27.2	NA	NA
Petiole, 75 DAE	71	21.6	213	32.5
Soil, 30 DAE	NA	NA	NA	NA
Soil, 60 DAE	301	91.9	218	33.1
Soil harvest, 0–1 ft ^y	50	8.2	204	23.0
Soil harvest, 0–3 ft	27	15.3	151	31.0
Mean	104	31.8	125	30.3
2001 ^v				
Tuber yield	NA	NA	NA	NA
Tuber N concentration	NA	NA	NA	NA
Tuber N uptake	NA	NA	NA	NA
Petiole, 26 DAE	156	51.0	188	34.9
Petiole, 36 DAE	NA	26.2	128	24.3
Petiole, 44 DAE	85	27.8	80	14.9
Petiole, 57 DAE	75	24.5	105	19.6
Soil, 26 DAE, 0–1 ft	75	25.8	96	17.9
Soil, 58 DAE, 0–1 ft	31	10.1	50	9.2
Soil harvest, 0–1 ft	54	17.6	157	29.1
Soil harvest, 0–3 ft	87	31.4	192	34.2
Mean	80	26.8	125	23.0

^xPetiole and soil values are nitrate-N.

^y1 lb/acre = 1.12 kg·ha⁻¹, DAE = days after emergence, 1 ft = 30.5 cm.

^z2000: low manure N content 328 lb/acre (367.4 kg·ha⁻¹), High manure N content 657 lb/acre (735.8 kg·ha⁻¹).

^wNA = unable to compute availability due to non significant regression equations or manure response values exceeding fertilizer response values.

^v2001: low manure N content 306 lb/acre (342.7 kg·ha⁻¹), High manure N content 539 lb/acre (603.7 kg·ha⁻¹).

Black, W.N. and R.P. White. 1973. Effects of nitrogen, phosphorus, potassium, and manure factorially applied to potatoes in a long-term study. *Can. J. Soil Sci.* 53:205–211.

Chambers, B.J., E.I. Lord, F.A. Nicholson, and K.A. Smith. 1999. Predicting nitrogen availability and losses following application of organic manures to arable land: MANNER. *Soil Use Mgt.* 15:137–143.

Gilbertson, C.B., J.A. Nienaber, J.L. Gartung, J.R. Ellis, and W.E. Splinter. 1979. Runoff control comparisons for commercial beef cattle feedlots. *Trans. Amer. Soc. Agr. Eng.* 22:842–846.

Grandy, A.S., G.A. Porter, and M.S. Erich. 2002. Organic amendment and rotation crop effects on the recovery of soil organic matter and aggregation in potato cropping systems. *Soil Sci. Soc. Amer. J.* 66:1311–1319.

Jemison, Jr., J.M. and R.H. Fox. 1994. Nitrate leaching from nitrogen-fertilized and manured corn measured with zero-tension pan lysimeters. *J. Environ. Qual.* 23:337–343.

Jokela, W.E. 1992. Nitrogen fertilizer and dairy manure effects on corn yield and soil nitrate. *Soil Sci. Soc. Amer. J.* 56:148–154.

Klausner, S.D. and R.W. Guest. 1981. Influence of NH₃ conservation from dairy manure on the yield of corn. *Agron. J.* 73:720–723.

Klausner, S.D., V. Rao-Kanneganti, and D.R. Bouldin. 1994. An approach for estimating a decay series for organic nitrogen in animal manure. *Agron. J.* 86:897–903.

Lachat Instruments. 1992a. Nitrate in 2M KCl soil extracts. Lachat Instruments, Milwaukee, Wis.

Lachat Instruments. 1992b. Total Kjeldahl nitrogen in soil/plant. Lachat Instruments, Milwaukee, Wis.

Lee, C.R. and M.L. MacDonald. 1977. Influence of soil amendments on potato growth, mineral nutrition, and tuber yield and quality on very strongly acid soils. *Soil Sci. Soc. Amer. J.* 41:573–577.

Liegel, E.A., C.R. Simson, and E.E. Schulte. 1980. Wisconsin procedures for soil testing, plant analysis and feed and forage analysis. Univ. Wis.-Madison Soil Fertility. Series No. 6 (revised).

Magdoff, F.R., D. Ross, and J. Amadon. 1984. A soil test for nitrogen availability to corn. *Soil Sci. Soc. Amer. J.* 48:1301–1304.

Motavalli, P.P., K.A. Kelling, and J.C. Converse. 1989. First-year nutrient availability from injected dairy manure. *J. Environ. Qual.* 18:180–185.

Powell, J.M. and Z. Wu. 1999. Nitrogen-15 labeling of dairy feces and urine for nutrient cycling studies. *Agron. J.* 91:814–818.

Powelson, M.L., K.B. Johnson, and R.C. Rowe. 1993. Management of diseases caused by soil-borne pathogens, p. 149–158. In: R.C. Rowe (ed.). *Potato health management*. APS Press, St. Paul, Minn.

Pratt, P.F., S. Davis, and R.G. Sharpless. 1976. A four-year field trial with animal manures. I. Nitrogen balances and yields. II. Mineralization of nitrogen. *Hilgardia* 44:99–125.

SAS Institute. 1990. SAS/Stat user's guide. Version 6. SAS Inst. Inc., Cary, N.C.

Sharma, R.C., J.S. Grewal, and M. Singh. 1980. Effects of annual and biennial applications of phosphorus and potassium fertilizer and farmyard manure on yields of potato tubers, on nutrient uptake and on soil properties. *J. Agr. Sci. (Cambridge)* 94:533–538.

Smith, J.H. and J.R. Peterson. 1982. Recycling of nitrogen through land application of agricultural, food processing, and municipal wastes, p. 791–831. In: F.J. Stevenson (ed.). *Nitrogen in agricultural soils*. Agron. 22. Amer. Soc. Agron., Madison, Wis.