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Implementation of Nutrient Management Planning on a Dairy Farm

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Abstract

*Environmental policy and highly variable margins are requiring major changes on dairy farms. A case study was conducted on a commercial dairy farm over a 5-yr period to evaluate the impact of implementing methods designed to improve environmental and economic sustainability. Six Sigma (Pande et al., 2000) principles were utilized in conjunction with the Cornell University Nutrient Management Planning System (**cuNMPS**) to develop a system for precision farming to improve nutrient management. Critical components were the development and implementation of plans for herd nutrient management and crop, soil, and manure nutrient management. Implementation of this precision farming system resulted in increases in animal numbers (26%), milk per cow (9%), total milk sold daily (45%), and decreases in purchased feed cost (48%), feed cost per kilogram of milk sold (52%), and total manure N (17%) and P (28%) excretion. These results were attributed to improvements in forage production, quality, and storage (38% increase in proportion of diets homegrown) and precision feeding of high forage diets using the Cornell University Net Carbohydrate and Protein System (**CNCPS**) for diet formulation. Implementation of this approach on other farms requires management commitment and training. Training must include providing background information and tools for making continuous improvement in quality control and management and the use of root cause analysis. The adoption of the precision farming system by the case study farm management team has improved the business financially and decreased the accumulation of manure nutrients per hectare.*

(Key Words: Quality Control, Nutrient Management, Dairy Farm Sustainability.)

Introduction

Nutrient management has become increasingly important since concentrated animal feeding operation (**CAFO**) regulations have been implemented in the United States (CFR, 2003). Currently, CAFO nutrient management planning is focused on crop nutrient management and how to deal with manure as a waste and (or) fertility product (CFR, 2003). Additional environmental regulations will continue to be developed and implemented in the United States. As we move toward control of air emissions from agriculture and the PM2.5 policy (particles greater than 2.5 μm in diameter, including ammonia), cattle nutrient excretion and nutrition will have a larger emphasis (Sweeten et al., 2000). The result will be an increased need for integrated nutrient management planning. Integrated nutrient management planning was developed to integrate crop production, animal production, and nutrient cycling to ensure economic and environmental sustainability (Tylutki and Fox, 1997, 1998).

In the last 10 yr, nutrient management and integrated nutrient management have been discussed many times (Bannon and Klausner, 1997; Kilcer, 1997; Tylutki and Fox, 1997; Pell, 1992; Klausner, 1993) with references being made to the Cornell University Nutrient Management Planning System (cuNMPS) (Tylutki and Fox, 1997; Tylutki and Klausner, 1995). The cuNMPS has evolved since 1995 to include two components: the Cornell Net Carbohydrate and Protein System version 5.0 (CNCPS) (Fox et al., 2003) and Cornell CropWare (Ketterings et al., 2001); both represent field-useable tools to develop integrated nutrient management plans on farms. Tylutki and Fox

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(1997) and Bannon and Klausner (1997) described their application in whole farm nutrient management planning. Beginning in 1997 (Yr 0), a study was initiated to evaluate the implementation of the cuNMPS on a commercial dairy farm and to identify changes needed to make these software tools more useful in nutrient management planning. The objectives of this paper were 1) to describe changes made in the case study farm to implement integrated nutrient management through the use of the cuNMPS models, 2) to discuss the impact these changes have had on the farm, and 3) to provide a framework for implementing this process on other farms.

Materials and Methods

Case Study Farm Description. McMahon's EZ Acres is a 650-cow dairy operation owned and managed by two brothers located in Homer, New York (42° 38″ North, 76° 10″ West). In December 1995, the herd was moved to a new 500-cow freestall facility. In 1997, the farm consisted of 435 tillable ha [43% maize and 57% combination alfalfa (Lucerne) and grass (mixed species) hay crop species] (Bannon and Klausner, 1997). The farm consists of a mix of level well-drained soils (gravel-based, valley-floor land) and moderately to poorly drained sloping soils (acidic clay-based hill land). The dairy complex is located on the valley floor above an aquifer that supplies the drinking water for approximately 50,000 people. Additionally, a naturally stocked brown trout stream runs the length of the valley floor and is monitored closely by the New York State Department of Environmental Conservation for sediment and algae growth. The hill land has a low leaching potential but a greater run-off potential that can enter tributaries of the trout stream. Since 1997, additional land has been acquired (purchased and rented) with the 2002 crop year consisting of 176 ha of maize, 142 ha of grass species, and 142 ha of alfalfa (460 ha total).

Implementation of Whole Farm Planning over 5 yr. The process of evaluating and implementing the cuNMPS on the case study farm was evolutionary; Tylutki (2002) provided complete details of changes made, procedures followed, and results. What began as a simple evaluation to be conducted over time resulted in a complex whole farm systems analysis with intervention required in all systems. Because of the data requirements of CAFOs and the software and needs identified during this case study, we began integrating manufacturing quality control principles in the software design (CNCPS and CropWare) and in training sessions for agri-industry and extension staff (Tylutki and Fox, 2000a,c, 2002). This integration led us to a new paradigm: precision farming. Precision farming consists of the use of precision in feeding management, crop management, animal management, and business management. As we worked with this case study, we learned that integrated whole-farm nutrient management using precision farming approaches can be regarded as an evaluation of the whole business (Tylutki and Fox, 2000b, 2002). Based on this finding, we outlined a whole-farm management scheme based on quality management and Six Sigma (Pande et al., 2000) theory. This scheme focuses on root cause analysis, continuous improvement, and shifting managers' thinking to a more holistic business management approach. Successful implementation required a thorough understanding of the farm as an integrated series of systems.

The objective of precision feeding is to predict animal requirements and feed biological values accurately on each farm so that diets can be formulated with less safety factor, managing associated production risks as described by Tylutki (2002). Precision feeding relies on using management practices that ensure the diet consumed by the cow is as close as possible to the formulated diet. Precision crop management integrates traditional crop nutrient management planning (manure and fertilizer planning) with additional data required from the nutritionist (desired forage quantity and quality goals) and the agronomist (to ensure that goals are met). Precision animal management focuses on cow health, comfort, and productivity to ensure that production, quality, and cow longevity goals are met. All of these goals required improved management in this case study; thus, we turned to Six Sigma for a proven management model (Pande et al., 2000; Tylutki and Fox, 2000b).

The primary changes made that facilitated the implementation of precision farming during the 5-yr of the case study are listed in Table 1. The farm has evolved to precision farming by following a continuous improvement paradigm with simple statistics and root cause analysis assisting management in decision making. Simple statistics have been introduced to provide a framework for data analysis and planning, and although the on-farm use is abbreviated, statistics selected for on-farm use (mean, standard deviation, feeder loading deviations, and I-charts (control charts) (Black, 1991)) are consistent with Six Sigma theory (Breyfogle, III, 1999).

Results and Discussion

Changes in Case Study Farm Production and Nutrients 1997–2002. In 1997, implementation of the cuNMPS in developing whole farm nutrient management planning was initiated, including an analysis of logical alternatives for the farm, as described previously (Bannon and Klausner, 1997; Kilcer, 1997; Tylutki and Fox, 1997). These results serve as the baseline data for this case study, which included 922 cattle (Table 2). Version 5 of the Cornell Net Carbohydrate and Protein System (CNCPSv5); (Fox et al., 2003) was utilized to evaluate nutrient adequacy and excretion using historical records allowing before and after implementation comparisons. Milk production was evaluated utilizing

TABLE 1. Summary of changes made during the 5-yr case study to facilitate the implementation of precision farming.

Year	Changes
0 (base)	Base data year Purchased 100 cows Began intensifying grass management
1	Began processing corn silage Hire young stock manager New harvester New mixer truck One partner leaves farm Started to store hay crops by type *vs* cutting
2	Added more fans Began bagging forages in excess of bunk capacity Began sprinkling cows in holding area Began temporal forage planning and allocation Began weekly group sampling for components Intensified grass management Many ration changes (CNCPS[a] based) More bags used (hay crop in addition to corn silage) Began storing hay crop by type (alfalfa *vs* grass) *vs* by cutting Began charting parlor performance Began charting weekly milk components Began charting feeder deviations Began charting forage DM Began charting cull rate Regrouped herd Started to see impact of intensive grass: shorter alfalfa and corn rotations on valley fields
3	Began developing Quality Manual Began developing Standard Operating Procedures Began discussing stretch goals Began reviewing farm via systems thinking New dry cow facility Full implementation of CNCPS target growth system for replacement heifers
4	Began using Latino labor Harvested 45 ha as dry corn Initiated budget planning (with stretch goals) followed by quarterly reviews New pull behind tank spreader (larger allowing for less trips) Replaced EZ-Feed™ with FeedWatch[b] Updated truck fleet; Ripple: needed larger corn head Utilized custom harvester to help with corn harvest
5	Altered hay crop harvest process to reduce soluble protein Began planning for methane digester/manure storage CAFO[c] plan developed Growing forages specifically for transition cows New corn silage bunk (no more bags) Planning started for next free-stall barn Renovated hospital barn stalls Started using activity for heat detection Two new used tractors

[a]CNCPS = Cornell Net Carbohydrate and Protein System.
[b]EZFeed™ (DHI-Provo, Provo, UT); Feedwatch (Valley Agricultural Software, Tulare, CA).
[c]CAFO = Concentrated animal feeding operation.

farm records and averaged 30.9 kg/cow in 1997 (Table 2). Annual herd size for Yr 0 was smaller than previously reported (Tylutki and Fox, 1997) and can be explained by the high cull rate the herd was experiencing (44%) and by analyzing the herd with annual data (multiple observations) *vs* test day (single observation). Predictions with the CNCPS (version 5) indicate that 42.9% of the diet, 19% of the N, and 22% of the P was homegrown (Table 3). Nutrient efficiency (product/total nutrient intake, where product is a combination of milk, growth, reserves, and conceptus) was 19% and 25% for N and P, respectively (Table 3). Current feed costs (June 2002) were used throughout the evaluation; Yr 0 feed costs were $2200 daily, including $1813 in purchased feed costs (Table 4). Total manure nutrient excretion (fecal plus urinary) was predicted to be 140,305 and 19,720 kg annually for N and P, respectively.

Kilcer (1997) calculated that maize silage storage losses exceeded 35% of total DM harvested. The storage loss was confirmed as Kilcer (1997) found a large discrepancy in the ratio of whole plant maize to hay crop forage harvested (73.6 to 26.4%) and fed amounts (64.8 to 35.2%). Bannon and Klausner (1997) and Kilcer (1997) concluded that the crop production scheme did not match the soil properties adequately, resulting in less than desired yields, excessive nutrient importations, and high costs of forage production. This result was of utmost importance to the farm managers, who previously believed they could not produce the herd forage needs with their land base.

Changes in the feeding and cropping systems to improve whole farm nutrient management resulted in large nutrient management impacts. Feeding system changes included a new bunk silo, improved bunk face management, covering the bunk adequately (including type of plastic and switching to tire sidewalls), routine DM determination of silages (minimum frequency of three times weekly), improved communication between feeders and management, setting goals for feeder deviations (sum of individual feeds over or under loading), development and implementation of a feeder checklist, control chart use by feeders, and routine maintenance schedules for feeding equipment. Additionally, a major shift in hay crop storage management occurred. Before precision farming was implemented, hay crop was stored by cutting (regardless of species); after precision farming was implemented, hay crop storage was segregated by species (grass in one bunk, alfalfa in another bunk). This change required a capital investment (a concrete apron); however, it provided feeding flexibility, allowing for four different hay crop silages to be fed simultaneously and allowing the maize silage bunk to be packed differently (gentle slope on each end *vs* steep slope on back end), which decreased storage losses. The farm systems changes have made temporal allocation of forages possible, allowing for decreased nutrient importations as a result of increased home grown feed quantity and quality.

Crop system changes included substituting intensive grass management for corn and alfalfa on the hill land, shorter rotations of alfalfa to corn on the valley land, and changes in forage harvest strategy. These crop management changes have resulted in improvements in forage yields, management of soil erosion, soil health, and pesticide use. Because of improved forage yields, forage harvest evolved to a quality needs basis, maximizing rumen function

TABLE 2. Herd parameters and progress over a 5-yr period.

Year	Herd size	Milking (no.)	Dry (no.)	Heifers (no.)	Milk (kg/d)	Milk (kg shipped/d)	Calving interval	Age of first calving (mo)	Cull rate (%)
0	852	408	70	374	30.9	12,596	NA[a]	NA	44.0
1	891	426	70	395	29.5	12,571	13.0	22.6	42.2
2	883	454	59	370	30.4	13,810	13.2	21.5	33.9
3	960	495	69	397	30.4	15,057	13.2	22.1	34.8
4	1007	507	81	419	32.2	16,343	13.4	22.3	31.6
5	1077	544	83	452	33.6	18,276	12.8	21.5	23.3
5 *vs* 0 (%)	126	133	119	121	109	145	NA	NA	53
5 *vs* 1 (%)	120	128	118	114	114	145	98	95	55
Slope	44.3	27.5	3.1	13.9	0.62	1170	–0.0	–0.1	–3.8
r^2 (%)	93	98	43	73	62	95	3	24	91

[a]NA indicates that data were not available. DairyComp 305 cowfiles began to be warehoused for this study starting in 1998.

and net energy intake from forage. Decisions on when to rotate from alfalfa to maize are currently based on first harvest NDF levels (>50% NDF, indicating a high grass content) *vs* producer perception (appearance similar to alfalfa).

Impact. The impact of implementing precision farming is summarized in Tables 2, 3, and 4. Total herd size increased 26% in 5 yr; most of this growth was due to decreased cull rates. Numerous changes impacted the cull rate, many of which were related to changes in management and nutrition of far-off dry and transition cows (new dry cow barn and diet formulations to maintain energy balance throughout the dry period). Although milk per cow has experienced a greater trend, late in Yr 1 and early in Yr 2, the herd was exhibiting clinical acidosis as a result of less dietary NDF and physically effective NDF levels prior to implementation of the CNCPS. For 9 mo following CNCPS implementation, milk per cow declined in a linear fashion to a low of 27.1 kg per cow, before it began to increase, with milk per cow reaching farm record maximums in 2002 (34.5 kg per cow until production was reduced by heat stress). Herd size increased by 44 cows annually over the 5 yr of the case study (Table 2). The combination of increased cow numbers and greater milk per cow resulted in 45% more milk shipped daily in the first 6 mo of Yr 5 *vs* Yr 0. Additionally, there were improvements in calving interval (13.6 mo in Yr 0, 12.9 mo in Yr 5) and average age at first calving. The CNCPS target growth rates and breeding weights were used to set strict goals for heifer management, which included a minimum breeding weight of 55% of mature weight (377 kg) at a moderate body condition score (3.0 to 3.5) and average age at first calving of 21.5 mo. Animal scales were installed to track heifer BW, including bred heifers precalving with a goal of 590 kg by 5 wk precalving to achieve 82% of mature BW postcalving. Heifer growth is tracked as carefully as milk production to maximize heifers available for replacements and herd growth without reducing first lactation milk production.

Changes to the cropping and feed storage systems have resulted in increased yields after storage. Yields after storage integrate storage losses with crop production. Bunk silo storage losses have been reduced to an estimated 18 to 20% *vs* 25 to 35% in Yr 0. Changes to crop rotations, fertility practices, and harvest strategy allowed harvested yields to continue along an upward trend (with exceptions for weather and pests). These changes resulted in a greater proportion of home grown forage in the diet (38%) when comparing Yr 5 and Yr 0 (Table 3). This difference would be greater if additional land were available to increase inventory, as the current diets average 0.85% of BW as forage NDF with a goal of 1% of BW to be achieved in the next 2 to 3 yr. Quality goals for forage are 50 to 52% NDF grass silage, 37 to 40% NDF alfalfa silage, and 37 to 42% NDF maize silage. Dry matter goals are 28 to 35% DM for grass silage, 37 to 45% for alfalfa, and 32 to 40% for maize silage. These goals are used for crop and ration planning as we continue to strive toward the NDF goal of 1% BW from forage.

As the proportion of forage in the diet increased, imported nutrients declined (Table 3). A large reduction in P imports occurred when all inorganic sources of P were removed from the diets. This herd has been fed diets with 0.25 to 0.37% P for over 3 yr, and herd performance has increased with no ill effects observed. As illustrated in Table 3, decreasing N and P levels in the diets has resulted in efficiency improvements. Nitrogen efficiency can be improved further (>30% goal), but P is likely to remain in the 35% range. Gains in N efficiency require changes in the crop harvest system to reduce the soluble protein levels of forages and then carefully match RUP sources with microbial protein to optimize amino acid supply to the small intestine. Large gains have been made in this area; however, further improvements can be made.

An added benefit of greater forage levels across the herd is a reduction in purchased feed cost (Table 4). Forage quality and quantity com-

TABLE 3. Improvements in proportion of diets home grown, N and P purchases, and efficiency of use (product/intake) over 5 yr.

	Proportion of diet		Purchased		Efficiency	
Year	Home grown	Purchased	N	P	N	P
	(%)					
0	43	57	81	78	19	25
1[a]						
2	49	51	64	64	26	30
3	48	52	62	64	21	27
4	55	45	61	54	24	31
5	59	41	51	47	25	35
5 *vs* 0	138	72	63	60	133	141
Slope	3.1	–3.1	–5.5	–6.0	0.9	1.8
r^2	89	89	93	97	38	75

[a]1998 diet information was not available.

TABLE 4. Feed cost and nutrients (N and P) in manure over a 5-yr period.

Item	Total feed cost/d	Purchased feed cost: Daily	Purchased feed cost: Per 45.4 kg of milk	Purchased feed cost: Per animal	Manure nutrient: N	Manure nutrient: N[a]	Manure nutrient: P	Manure nutrient: P[a]
Year					(kg/ha)			
0	$2200	$1813	$6.56	$2.13	140,306	322	19,720	43
1								
2	$1982	$1396	$4.62	$1.58	100,441		15,035	
3	$2517	$1462	$4.38	$1.52				
4	$2514	$1508	$4.21	$1.50				
5	$2467	$1375	$3.42	$1.28	116,382	268	14,161	31
5 *vs* 0 (%)	112	76	52	60	83	83	72	72
Slope	$81	–$72	–$0.58	–$0.16	–3987		–1047	
r^2 (%)	43	61	92	90	25		78	

[a]Loading rates were calculated only for 1997 and 2002 to highlight change in loading pre- and post-implementation. Manure N and P are reported only for 1997 (pre-implementation), 1999 (first year of Cornell University Carbohydrate and Protein System formulation on-farm), and 2002 (post-implementation).

bined with safety factor reduction attributable to precision feeding have allowed the farm to capture a 50% reduction in purchased feed cost per 45.4 kg of milk. The reliance on more forage and reductions in diet safety factors comes with risk; shifts in forage quality, failure to determine and adjust for DM routinely, and inadequate feeding management result in increased production variability (Tylutki, 2002). This fact was observed in 2001 when the farm was switching feed truck scale interface software. For several weeks, the feeders were forced to feed from manually calculated feed sheets while new hardware and software was being installed. During this time, feed sheets were being updated for silage DM incorrectly, and daily milk production analysis indicated that milk per cow varied within a 2-kg range. Less than a 0.5-kg range is normal for this herd when rations are deemed in control. It was also observed during this time that milk urea N was greater and varied more (12 to 17 mg/dL) compared with typical ranges of 11 to 13 mg/dL.

Total manure nutrients have also been reduced (Table 4) compared with Yr 0 values. Manure N has been reduced less than manure P; however, as more forage is fed, maintenance protein requirements increase, and forage N digestibility is typically less than concentrates. When assessing nutrient management, this shift marks an impact on the type of N excreted. More organic N is excreted, which is more stable in the environment than ammonia N (from urine), which will be volatilized. The net effect, however, of greater home grown forage diets was a 17% less N loading rate (kg/ha) in Yr 5 *vs* Yr 0. Phosphorus accumulation per hectare has decreased 28% and is a direct result of decreased dietary P and less purchased feed, primarily protein sources. High protein feeds, such as soybean meal, also tend to be high in P; thus, improved forage quality and quantity fed result in less P importations as well. As total home grown feed levels have increased, and total N and P purchases decreased, and the proportion of dietary N and P being recycled within the farm is increasing. As an example, if alfalfa silage averaged 0.30% P and yielded 4.48 mt DM/ha, this removes 13.4 kg P annually, and the farm is currently applying an average of 13.7 kg/ha from manure. This procedure means that the farm is accumulating P at a rate of 0.3 kg/ha in 2002 *vs* 8.1 kg/ha in Yr 0.

Nitrogen efficiency at the farm level continues to be addressed. The next step is the construction of covered manure storage, which should allow for less commercial fertilizer application on the grass and corn for silage, thereby improving whole farm N efficiency. Annual forage inventory levels still need to be increased, but this requires additional land. The next expansion step is planned for 2004 (requiring even more land).

A simple consultant checklist was developed from this case study (Table 5). The checklist illustrates the level of communication that must occur between consultant and farm and on

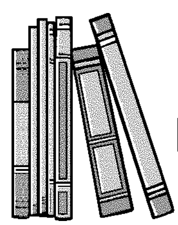
TABLE 5. Farm management checklist.

Upper management level discussions	Middle management, other employees, and other topics
Review the general farm information annually	Talk with feeder monthly including
Review labor force quarterly	Review DMI by group
Establish the farm goals, including where the farm wants to be in 5 and 10 yr	Review silo management
Flow chart the farm	Are DMs[a] done as scheduled
Review farm logistics	Review feeder Standard Operating Procedures quarterly
Identify the technical team on the farm	Review lactating herd performance monthly
How does general management think and work	Review replacement herd performance monthly
Communicate with management monthly	Review dry cow program monthly
Are control charts being updated monthly	Talk with herds people to get their view on current status monthly
Are control charts being updated	Check mixer for weight accuracy and operation
Analyze charts for trends	Check mixer via mixer test quarterly
Review hay harvest number (after each cutting)	Talk with hoof trimmer quarterly
Review current cutting	Listen to what veterinarian has to say quarterly
Was N land applied for next hay harvest	Check inventory of forages and contracts quarterly at a minimum
Plan where to put next harvest	Temporal allocation of forages
Corn harvest	Fall equipment issues
Is chopper ready for corn	Is the equipment ready for winter
Determine corn field harvest order	What equipment maintenance is needed
Check packing of corn	Equipment purchase planning
Check particle size of corn	Spring equipment issues
Watch packing height of corn	Is tillage equipment ready
Review corn harvest	Was N applied to grass in early spring
Review hay crop overall including yields	Is plastic available to cover hay crops
Plan commodity purchases	Is hay equipment ready
Begin next years planning	Next year's planning continued
Herd size projections for next 12 mo	How much corn do we want
Will we have enough storage	How much hay crop do we want
Begin inventory allocation planning	What kind of corn do we want
How much forage should we feed for next 12 mo	Corn seed ordered
Anything storage we need to change for next year	
How many hectares will be needed	

the farm between management and employees. Successful implementation of precision farming based on Six Sigma principles requires this level of management commitment (Pande et al., 2000; Tylutki and Fox, 2002). Farm systems such as this one are continuously changing and require monitoring and updating of plans to take into account the ripples introduced by expansion or other changes.

Implications

Implementation of integrated whole farm nutrient management and the use of precision farming can improve profitability, reduce excess nutrients per hectare of land, and reduce the risk of their loss to the environment. Integrating scientific knowledge into computer tools allows the use of the best science in developing precision feeding and cropping plans that optimize herd and crop production with the minimum nutrients necessary to maximize production. The use of quality management principles in implementing these plans allows the reduction of nutrient safety factors and results in human management needed to optimize animal and soil productivity.



Literature Cited

Bannon, C. D., and S. D. Klausner. 1997. Application of the Cornell Nutrient Management Planning System: Predicting crop requirements and optimum manure management. In Proc. 1997 Cornell Nutr. Conf. Feed Manufacturers. p 36. Dep. Anim. Sci., Cornell Univ., Ithaca NY.

Black, J. T. 1991. The Design of the Factory with a Future. (1st Ed.). McGraw-Hill, Inc, New York.

Breyfogle, III, F. W. 1999. Implementing Six Sigma: Smarter Solutions Using Statistical Methods. John Wiley & Sons, New York.

Code of Federal Regulations, 2003. National pollutant discharge elimination system permit regulation and effluent limitation guidelines and standards for concentrated animal feeding operations (CAFOs), Code of Federal Regulations, Title 29, Vol. 68, Section 40 CFR Parts 9, 122, 123, and 412. p 7176. Available at: http://www.epa.gov/npdes/regulations/cafo_fedrgstr.pdf. Accessed October 30, 2003.

Fox, D. G., T. P. Tylutki, L. O. Tedeschi, M. E. Van Amburgh, L. E. Chase, A. N. Pell, T. R. Overton, and J. B. Russell. 2003. The net carbohydrate and protein system for evaluating herd nutrition and nutrient excretion. AnSci Mimeo 213. p 1. Dep. Anim. Sci., Cornell Univ., Ithaca, NY.

Ketterings, Q., G. A. Albrecht, K. Czymmek, C. N. Rasmussen, and V. M. Durbal. 2001. Cornell Cropware. Dep. Crop and Soil Sci. and Anim. Sci., Cornell Univ., Ithaca, NY.

Kilcer, T. 1997. Application of the Cornell Nutrient Management Planning System: Optimizing crop rotations. In Proc. 1997 Cornell Nutr. Conf. Feed Manufacturers. p 45. Dep. Anim. Sci., Cornell Univ., Ithaca NY.

Klausner, S. D. 1993. Mass nutrient balances on dairy farms. In Proc. 1993 Cornell Nutr. Conf. Feed Manufacturers. p 126. Dep. Anim. Sci., Cornell Univ., Ithaca NY.

Pande, P. S., R. P. Neuman, and R. R. Cavanagh. 2000. The Six Sigma Way. How GE, Motorola, and Other Top Companies are Honing Their Performance. McGraw-Hill, New York.

Pell, A. N. 1992. Does ration balancing affect nutrient management? In Proc. 1992 Cornell Nutr. Conf. Feed Manufacturers. p 23. Dep. Anim. Sci., Cornell Univ., Ithaca, NY.

Sweeten, J. M., L. Erickson, P. Woodford, C. B. Parnell, K. Thu, T. Coleman, C. Reeder, J. R. Master, W. Hambleton, G. Bluhm, and D. Tristao. 2000. Air quality research and technology transfer white paper and recommendations for concentrated animal feeding operations. USDA Agric. Air Quality Task Force, Washington, DC.

Tylutki, T. P. 2002. Improving herd nutrient management on dairy farms: 1) Individual cow milk production variance. 2) Developing a quality management program on a commercial dairy farm: A six sigma approach. 3) Variation in nutrient content of feeds on a commercial dairy farm. 4) Predicting phosphorus excretion by dairy cattle. 5) Incorporating risk in managing dairy cattle nutrition. Ph.D. Diss., Cornell Univ., Ithaca, NY.

Tylutki, T. P., and D. G. Fox. 1997. Application of the Cornell Nutrient Management Planning System: Optimizing herd nutrition. In Proc. 1997 Cornell Nutr. Conf. Feed Manufacturers. p 54. Dep. Anim. Sci., Cornell Univ., Ithaca, NY.

Tylutki, T. P., and D. G. Fox. 1998. Dairy farming and water quality II: Whole farm nutrient management planning. In NRAES Dairy Feeding Systems Conf. p 345. Nat. Res., Agric., Eng. Serv., Coop. Ext., Ithaca, NY.

Tylutki, T. P., and D. G. Fox. 2000a. An integrated cattle and crop production model to develop whole-farm nutrient management plans. In Modeling Nutrient Utilization in Farm Animals. J. P. McNamara (Ed.). p 253. CABI Publ., New York.

Tylutki, T. P., and D. G. Fox. 2000b. Managing the dairy feeding system to minimize manure nutrients. In Managing Nutrients and Pathogens from Animal Agriculture. p 209. Nat. Res., Agric., Eng. Serv., Coop. Ext., Ithaca, NY.

Tylutki, T. P., and D. G. Fox. 2000c. Quality control in herd nutrient management. In Proc. 2000 Cornell Nutr. Conf. Feed Manufacturers. p 130. Dep. Anim. Sci., Cornell Univ., Ithaca, NY.

Tylutki, T. P., and D. G. Fox. 2002. Mooving towards Six Sigma. Q. Progress (Feb.): 34.

Tylutki, T. P., and S. D. Klausner. 1995. The Cornell Nutrient Management Planning System. Agron. Abstr. p 258.