Climate smart dairy and beef*

Frank M. Mitloehner, Professor and Air Quality CE Specialist
Department of Animal Science, University of California, Davis,2151 Meyer Hall, One Shields Ave, Davis, CA 95616, fmmitloehner@ucdavis.edu

Introduction

Production efficiency in the dairy and beef industry can be defined as minimizing the amount of inputs (e.g., feed, fossil fuels) and outputs (e.g., ammonia, NH_3; greenhouse gases, GHG) to produce a given quantity of milk or meat. The present paper will focus on the dairy example. Production efficiency improvements can come from minimizing waste, maximizing a dairy cow's milk production, and maximizing the proportion of her life spent in peak milk production without sacrificing animal health and well-being. To a degree, when milk production per cow is improved, the life-cycle emissions of dairy production decrease per unit of milk (i.e., per lb or kg of 3.5% FCM).[59] This is achieved through a dilution of maintenance costs per pound of FCM at the level of both the individual cow and the entire US dairy production system. Cows that produce more milk reduce the proportion of total consumed feedstuffs going toward maintenance energy costs.[4,40,58] Secondarily, more milk per cow can decrease the total lactating herd size needed to produce a given quantity of milk.[10,11] Past improvements demonstrate the ability of production efficiency to decrease the environmental impact per unit of milk. Capper et al[10] found that historical advances in genetics, nutrition, and management of dairy farms allowed dairy production in 2007 to emit 43% of the CH_4 and 56% of the N_2O that were emitted in 1944 to produce 2.2 billion (1 billion kg) of milk. As the following sections demonstrate, more opportunities for improving a dairy's production efficiency exist that could lead to further reductions in emissions per pound of FCM.

Heifer Management

Replacement heifers are an important part of the life-cycle emissions of a pound of FCM. Before calving, heifers are consuming inputs and producing both GHG and air pollutants without contributing to the production of milk. In the milk-fed stage of a heifer's life, she can efficiently convert consumed energy and protein into lean body tissue without depending on emission-producing rumen microbes.

Recent research has found that increasing and altering the nutrients supplied to milk-fed calves can improve growth rates and feed efficiency.[3,8,28] "Intensified" feeding programs for dairy heifers have been shown to lower age at first calving,[48] with no reduction[57] or even an improvement in first-lactation milk yield.[18] Both decreasing the current national average age at first calving of 25.2 months[56] and increasing first-lactation milk yield could improve milk's life-cycle production efficiency and decrease emissions per pound of FCM.

Colostrum administration is another aspect of heifer management that can affect GHG and air quality emissions per pound of FCM. Dairy calves depend on passive immunization from the absorption of antibodies in colostrum to provide adequate immunity during their early life stages.[49] Failure of passive transfer of immunity leads to increased mortality and morbidity and decreased growth performance.[5,49] Administering the proper quantity of high quality colostrum within the first few hours of life has been shown to improve long-term animal health and first-lactation performance.[16,20] Beam et al[5] estimated that failure of passive transfer occurs in 19.2% of US dairy heifer calves; therefore, decreasing this incidence could substantially decrease death and performance losses and lessen emissions per pound of FCM.

Herd Health

Herd-health challenges affect per-unit of-milk emissions by increasing mortality and losses of saleable milk and decreasing reproductive performance and milk production efficiency. Herd health is influenced by many factors, including management, nutrition, the environment, and social stressors.

Over the past 25 yr, the dairy industry has steadily shifted its structure toward fewer farms with larger herds and fewer workers per cow. In 2008, a total of 3,350 US dairy farms with 500 or more cows (approximately 5% of total dairy operations) produced 58.5% of the nation's milk with 54.9% of the nation's dairy cows.[41] Along with the industry's consolidation, milk production per cow has doubled over the past 25 yr, although it appears that disease incidence has remained stable.[37] However, the productive life of Holsteins in the US born in 2000 decreased by 3.95 months compared with Holstein cows born in 1980.[15] Thus, opportunities exist for the dairy industry to advance production efficiency by improving herd health to simultaneously enhance milk production, reproductive performance, and cow longevity.

When dairy cattle transition from a pregnant, non-lactating state to a lactating state, they face a tremendous change in their metabolic requirements (e.g., Ca requirements are estimated to increase 4-fold on the day of parturition).[46] Consequently, most health concerns arise during the transi-

*Excerpts from: Place SE, Mitloehner FM. Contemporary environmental issues: A review of the dairy industry's role in climate change and air quality and the potential of mitigation through improved production efficiency. Department of Animal Science, University of California, Davis, One Shields Ave., Davis, CA 95616-8521

tion period. Approximately 75% of disease occurs within the first month after calving,[37] and a study of Pennsylvania dairy herds found that 26.2% of dairy culls occur from 21 d before to 60 d after calving.[15] Recent research has linked disease incidence and excessive negative energy balances during the transition period with significant decreases in milk yield and reproductive success during the subsequent lactation.[17] Further research into the biology and management of transition cows and the extension of this critical knowledge to commercial herds can enhance the life-cycle efficiency of the US dairy production system.

Environmental or social stressors can decrease the production efficiency of the cow and subsequently increase the emissions of each pound of milk that she produces. Heat stress has been estimated to cost the dairy industry nearly $1 billion per year in decreased milk production, reproductive performance, and increased death losses.[52] With regard to social stress, grouping animals according to size and age and minimizing overcrowding can improve DMI, consequentially improving milk production.[24] Improving cow cooling during hot summer months and grouping animals to minimize behavioral stress has been the focus of research to improve farm profitability, but these improvements have the potential to decrease emissions per pound of FCM as well.

Mastitis is a herd-health challenge that can affect emissions per pound of FCM by decreasing milk production performance and increasing losses of saleable milk. Hospido and Sonesson[30] analyzed the environmental impact of mastitis using an LCA of dairy herds in Galicia, Spain. The authors found that decreasing the clinical mastitis rate from 25 to 18% and the subclinical mastitis rate from 33 to 15% reduced the GWP of a unit of milk by 2.5%[30] because of increased input-use efficiency, decreased losses of milk production, and a decreased amount of waste milk.

Lameness is a critical herd-health concern that seems to have worsened over the past 25 yr.[37] Lameness or injury is responsible for approximately 20% of mortalities and 16% of selective culls in mature US dairy cows.[56] In addition to decreased survivability, lameness causes decreased milk production[61] and poorer reproductive performance in affected cows.[21] Improved facilities, management, nutrition, and genetics all have the potential to decrease the incidence of lameness[2] and decrease emissions per pound of FCM.

Nutrition and Feed Production

The nutrition of dairy cattle greatly determines the emissions produced directly by the ruminant animal and its waste. Diet composition can alter rumen fermentation to reduce the amount of CH4 produced[19] and, as previously discussed, the NH3 emissions produced from the manure.[33,59] The substrates used by methanogens are byproducts of structural carbohydrate fermentation; thus, high-concentrate diets containing more nonstructural carbohydrates can lead to decreased CH4 emissions.[19,36] However, diets very high in concentrate (such as those fed to the majority of US beef feedlot cattle) can decrease rumen pH and lead to rumen acidosis.[47] Furthermore, very high-concentrate diets diminish the principal environmental benefit of dairy cows: their ability to convert cellulose, indigestible to humans and the Earth's most abundant organic molecule, into high-quality proteins for human consumption.[45]

Therefore, the CH4 produced by dairy cattle cannot simply be seen as a gross energy loss and GHG source but is a necessary consequence of transforming inedible fibrous forages and byproducts (e.g., almond hulls, citrus pulp, distillers grains) into food and fiber products fit for human use. Nonetheless, substantial reductions in CH4 emissions can be achieved without feeding high levels of concentrates by altering the previously mentioned nutritional factors: microbial-altering feed additives, dietary lipids, and forage processing and quality.[34]

Feed additives, such as the ionophore monensin, can change microbial processes in the rumen to potentially improve feed efficiency and reduce CH4 emissions.[54] However, research with monensin has shown conflicting results,[25,26,29,44] which suggests a need for more indepth research on its effect on rumen microbial populations and the metabolism of dairy cows. Alternatives to ionophores such as probiotics (e.g., yeast), essential oils, and biologically active plant compounds (e.g., condensed tannins) have shown promise for CH4 reductions; however, most research to date has been conducted in vitro and more in vivo studies are needed to evaluate the effect of these alternatives on CH4 and their commercial viability.[6,9]

Dietary lipids, specifically unsaturated fatty acids, have the potential to act as an alternate H sink in the rumen, thereby reducing the H available to methanogens and the CH4 produced.[19] Additionally, CH4 reductions from feeding dietary lipids can be attributed to their suppression of fiber-digesting bacteria and toxicity to protozoa closely associated with methanogens.[31] Johnson et al[35] tested the ability of canola and whole cottonseed to reduce CH4 and found no difference in emissions when compared with a control diet, whereas other researchers have found crushed canola seed to have a CH4-suppressing effect.[7] The inconsistency of the effect of dietary lipids on CH4 is due, in part, to the variation in diets, the fatty acid profile, amount and form of the lipid source, and the length of the feeding trial, because the rumen ecosystem may adapt to lipid supplementation.[7,39] Although lipids do have the potential to reduce CH4 emissions, consideration must be given to their adverse side effects of reducing DMI or decreasing milk fat when fed at levels over a critical threshold.[23,39]

Furthermore, the source and availability of lipids must be considered, because price will dictate their commercial adoption, and long-distance transport of lipid sources may defeat their emission-reducing potential by increasing fossil fuel combustion.

Forage quality and management can affect both air quality and GHG emissions per pound of FCM. Fermented feeds are a major source of VOC[1] and require substantial fossil fuel inputs during their production;[13,51] therefore, minimizing dry matter loss throughout the production, storage, and feeding of these feedstuffs will decrease the air quality and climate change impact of each pound of feed. Higher quality forages, produced by ideal crop production, harvesting, and preservation practices, maximize DMI and milk production.[43] Additionally, forages with higher digestibility and higher rates of passage out of the rumen have the potential to reduce enteric CH4 emissions for each unit of feed consumed.[34]

So-called precision feeding that closely matches the nutrients needed by the dairy cow for maintenance, growth, lactation, and gestation to the supplied dietary nutrients can minimize the environmental impact of the cow's excreta.[55] Precision feeding requires nutritional models with sufficient accuracy and a level of management that can reduce the feeding system's variation.[60] By constantly monitoring the dry matter and nutrient composition of feedstuffs, dairy producers can avoid expensive overfeeding and minimize nutrient excretion that can lead to emissions.

The potential reduction in NH3 emissions by more tightly managing the CP content of the diet to match the animal's needs is substantial, because most of the N fed over requirements is excreted as urinary urea-N. Castillo et al[12] found that cows with intakes of 419 g of N/d had similar milk production as cows consuming 516 g of N/d; however, 74% of the extra 94 g of N/d was excreted as urinary urea-N, which could be lost to the environment as NH3 emissions. Moreover, a precision feeding strategy decreases the amount of refusals, which may become waste on a dairy or be fed to other production groups (e.g., lactating cow refusals fed to heifers) that have dissimilar nutrient needs, thereby increasing the likelihood for higher nutrient excretion.[53] Additionally, closely monitoring and ensuring the correct nutrition of individual groups of animals can minimize the risk of other nutritionally influenced diseases and conditions, such as ketosis, lameness, and prolonged anestrous.[38] Overall, managing feed and feeding programs to minimize waste while maximizing milk production can improve farm profitability and decrease the life-cycle emissions per pound of FCM.

Reproduction

Perhaps not as apparent as nutrition, reproductive performance greatly affects emissions per pound of FCM. Dairy cows that have extended calving intervals because of conception failure spend more time out of peak milk when feed conversion into milk is most efficient. The total productive lifetime of many dairy cows is determined by reproductive performance, because reproductive problems are responsible for 26.3% of the selective culls in the United States.[56] Over the past 30 yr, the reproductive performance and productive lifetime of dairy cattle have substantially decreased while milk production has increased.[15,38] The negative effect per pound of FCM emissions caused by declining reproductive efficiency has likely been offset by increases in milk production per cow. However, restoring reproductive performance in combination with increased milk yield would further reduce emissions per pound of FCM.

Garnsworthy[22] modeled the environmental impact of reproductive performance and milk production in the United Kingdom. The model found that both higher milk yield and improved reproductive performance (better estrus detection and conception rates) contributed to reduced CH4 and NH3 emissions because of the smaller lactating and replacement herd population required to meet UK production quotas.[22]

The cause of the decline in reproductive efficiency of dairy cattle is multifaceted and is not completely understood currently,[32] because reproductive success is influenced by nutrition, genetics, health disorders during transition, management, and the environment.[38] The level of reproductive success across all US herds is variable by region, breed, and management,[42] suggesting that improvements are achievable.

Encouragingly, recent data show that the long-term trend of decreasing reproductive performance and survivability may be slowing or reversing.[27,42] Extensive research in dairy cattle reproduction is needed to identify the factors impeding fertility and to further develop strategies to improve reproduction on commercial herds. Wide adoption of these successful reproductive strategies could potentially lengthen the productive life of the US dairy cow and lower emissions per pound of FCM.

Sexed semen is a reproductive technology that has the potential to both help and hurt the impact of the dairy industry on air quality and climate change per pound of FCM. If used selectively, sexed semen can increase the rate of genetic gain in dairy cattle, allowing advantageous traits to become ubiquitous in the entire dairy cattle population.[14] Furthermore, on average, heifer calves are smaller than bull calves and cause fewer dystocias, which may allow for earlier breeding of heifers, and fewer mortalities and health problems.[62] However, if all animals are bred with sexed semen (or even all heifers), the replacement population for the US dairy herd will increase in size.

To keep the total population of dairy cattle at a level that does not create an oversupply of milk, the lactating cow cull rate must increase. Again, this can be advantageous, because poor performing animals and those with poor genetic merit would likely be culled, but in the context of environmental impact per pound of FCM, the widespread use of sexed semen could increase emissions per pound of FCM by shortening the total productive lifetime of dairy cows. Furthermore, a larger replacement herd size means more nonproductive emissions for each pound of FCM produced.

Conclusions

Overall, this paper shows that some of the most important gains that can be achieved in mitigation of dairy environmental impacts are tightly connected to efficiencies around feed and feeding as well as reproductive management.

References

1. Alanis P, Sorenson M, Beene M, Krauter C, Shamp B, Hasson AS. Measurement of non-enteric emission fluxes of volatile fatty acids from a California dairy by solid phase microextraction with gas chromatography/mass spectrometry. *Atmos Environ* 2008; 42:6417–6424.

2. Baird LG, O'Connell NE, McCoy MA, Keady TWJ, Kilpatrick DJ. Effects of breed and production system on lameness parameters in dairy cattle. *J Dairy Sci* 2009; 92:2174–2182.

3. Bascom SA, James RE, McGilliard ML, Van Amburgh ME. Influence of dietary fat and protein on body composition of Jersey bull calves. *J Dairy Sci* 2007; 90:5600–5609.

4. Bauman DE, McCutcheon SN, Steinhour WD, Eppard PJ, Sechen SJ. Sources of variation and prospects for improvement of productive efficiency in the dairy cow: A review. *J Dairy Sci* 1985; 60:583–592.

5. Beam AL, Lombard JE, Kopral CA, Garber LP, Winter AL, Hicks JA, Schlater JL. Prevalence of failure of passive transfer of immunity in newborn heifer calves and associated management practices on US dairy operations. *J Dairy Sci* 2009; 92:3973–3980.

6. Beauchemin KA, McAllister TA, McGinn SM. Dietary mitigation of enteric methane from cattle. CAB Reviews: Perspectives in Agriculture, Veterinary Science. *Nutr Nat Resour* 2009; 35:1–18.

7. Beauchemin KA, McGinn SM, Benchaar C, Holtshausen L. Crushed sunflower, flax, or canola seeds in lactating dairy cow diets: Effects on methane production, rumen fermentation, and milk production. *J Dairy Sci* 2009; 92:2118–2127.

8. Brown EG, VandeHaar MJ, Daniels KM, Liesman JS, Chapin LT, Keisler DH, Weber Nielsen MS. Effect of increasing energy and protein intake on body growth and carcass composition of heifer calves. *J Dairy Sci* 2005; 88:585–594.

9. Calsamiglia S, Busquet M, Cardozo PW, Castillejos L, Ferret A. Invited review: Essential oils as modifiers of rumen microbial fermentation. *J Dairy Sci* 2007; 90:2580–2595.

10. Capper JL, Cady RA, Bauman DE. The environmental impact of dairy production: 1944 compared with 2007. *J Dairy Sci* 2009; 87:2160–2167.

11. Capper JL, Castaneda-Gutierrez E, Cady RA, Bauman DE. The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. *Proc Natl Acad Sci* USA 2008; 105:9668–9673.

12. Castillo AR, Kebreab E, Beever DE, Barbi JH, Sutton JD, Kirby HC, France J. The effect of protein supplementation of nitrogen utilization in lactating dairy cows fed grass silage diets. *J Dairy Sci* 2001; 79:247–253.

13. de Boer IJM. Environmental impact assessment of conventional and organic milk production. *Livest Prod Sci* 2003; 80:69–77.

14. De Vries A, Overton M, Fetrow J, Leslie K, Eicker S, Rodgers G. Exploring the impact of sexed semen on the structure of the dairy industry. *J Dairy Sci* 2008; 91:847–856.

15. Dechow CD, Goodling RC. Mortality, culling by sixty days in milk, and production profiles in high- and low-survival Pennsylvania herds. *J Dairy Sci* 2008; 91:4630–4639.

16. DeNise SK, Robison JD, Stott GH, Armstrong DV. Effects of passive immunity on subsequent production in dairy heifers. *J Dairy Sci* 1989; 72:552–554.

17. Drackley JK. Biology of dairy cows during the transition period: The final frontier? *J Dairy Sci* 1999; 82:2259–2273.

18. Drackley JK, Pollard BC, Dann HM, Stamey JA. First-lactation milk production for cows fed control or intensified milk replacer programs as calves. *J Dairy Sci* 2007; 90(Suppl. 1):779. (Abstr.).

19. Ellis JL, Dijkstra J, Kebreab E, Bannink A, Odongo NE, McBride BW, France J. Aspects of rumen microbiology central to mechanistic modeling of methane production in cattle. *J Agric Sci* 2008; 146:213–233.

20. Faber SN, Faber NE, McCauley TC, Ax RL. Case study: Effects of colostrum ingestion on lactation performance. *Prof Anim Sci* 2005; 21:420–425.

21. Garbarino EJ, Hernandez JA, Shearer JK, Risco CA, Thatcher WW. Effects of lameness on ovarian activity in postpartum Holstein cows. *J Dairy Sci* 2004; 87:4123–4131.

22. Garnsworthy PC. The environmental impact of fertility in dairy cows: A modeling approach to predict methane and ammonia emissions. *Anim Feed Sci Technol* 2004; 112:211–223.

23. Giger-Reverdin S, Morand-Fehr P, Tran G. Literature survey of the influence of dietary fat composition on methane production in dairy cattle. *Livest Prod Sci* 2003;V82:73–79.

24. Grant RJ, Albright JL. Effect of animal grouping on feeding behavior and intake of dairy cattle. *J Dairy Sci* 2001; 84(E Suppl.):E156–E163.

25. Guan H, Wittenberg KM, Ominski KH, Krause DO. Efficacy of ionophores in cattle diets for mitigation of enteric methane. *J Anim Sci* 2006; 84:1896–1906.

26. Hamilton SW, DePeters EJ, McGarvey JA, Lathrop J, Mitloehner FM. Greenhouse gas, animal performance, and bacterial population structure responses to dietary monensin fed to dairy cows. *J Environ Qual* 2009; 39:106–114.

27. Hare E, Norman HD, Wright JR. Survival rates and productive herd life of dairy cattle in the United States. *J Dairy Sci* 2006; 89:3713–3720.

28. Hill SR, Knowlton KF, Daniels KM, James RE, Pearson RE, Capuco AV, Akers RM. Effects of milk replacer composition on growth, body composition, and nutrient excretion in preweaned Holstein heifers. *J Dairy Sci* 2008; 91:3145–3155.

29. Hook SE, Northwood KS, Wright A-DG, McBride BW. Long-term monensin supplementation does not significantly affect quantity or diversity of methanogens in the rumen of lactation dairy cattle. *Appl Environ Microbiol* 2009; 75:374–380.

30. Hospido A, Sonesson U. The environmental impact of mastitis: A case study of dairy herds. *Sci Total Environ* 2005; 343:71– 82.

31. Hristov AN, Vander Pol M, Agle M, Zaman S, Schneider C, Ndegwa P, Vaddella VK, Johnson K, Shingfield KJ, Karnati SKR. Effect of lauric acid and coconut oil on ruminal fermentation, digestion, ammonia losses from manure, and milk fatty acid composition in lactating cows. *J Dairy Sci* 2009; 92:5561–5582.

32. Ingvartsen KL, Dewhurst RJ, Friggens NC. On the relationship between lactational performance and health: Is it yield or metabolic imbalance that cause production diseases in dairy cattle? A position paper. *Livest Prod Sci* 2003; 83:277–308.

33. James T, Meyer D, Esparza E, DePeters EJ, PerezMonti H. Effects of dietary nitrogen manipulation on ammonia volatilization from manure from Holstein heifers. *J Dairy Sci* 1999; 82:2430–2439.

34. Johnson, K. A., and D. E. Johnson DE. 1995. Methane emissions from cattle. *J Dairy Sci* 1995; 73:2483–2492.

35. Johnson KA, Kincaid RL, Westberg HH, Gaskins CT, Lamb BK, Cronrath JD. The effect of oilseeds in diets of lactating cows on milk production and methane emissions. *J Dairy Sci* 2002; 85:1509–1515.

36. Lana RP, Russell JB, Van Amburgh ME. The role of pH in regulating ruminal methane and ammonia. *J Dairy Sci* 1998; 76:2190–2196.

37. LeBlanc SJ, Lissemore KD, Kelton DF, Duffield TF, Leslie KE. Major advances in disease prevention in dairy cattle. *J Dairy Sci* 2006; 89:1267–1279.

38. Lucy MC. Reproductive loss in high-producing dairy cattle: Where will it end? *J Dairy Sci* 2001; 84:1277–1293.

39. Martin C, Rouel J, Jouany JP, Doreau M, Chilliard Y. Methane output and diet digestibility in response to feeding dairy cows crude linseed, extruded linseed, or linseed oil. *J Anim Sci* 2008; 86:2642–2650.

40. Moe PW, Tyrrell HF. Efficiency of conversion of digested energy to milk. *J Dairy Sci* 1975; 58:602–610.

41. NASS. Farms, land in farms, and livestock operations: 2008 summary. http://usda.mannlib.cornell.edu/usda/current/ FarmLandIn/FarmLandIn-02-12-2009.pdf. Accessed Aug. 23, 2009.

42. Norman HD, Wright JR, Hubbard SM, Miller RH, Hutchison JL. Reproductive status of Holstein and Jersey cows in the United States. *J Dairy Sci* 2009; 92:3517–3528.

43. Oba M, Allen MS. Evaluation of the importance of the digestibility of neutral detergent fiber from forage: Effects on dry matter intake and milk yield of dairy cows. *J Dairy Sci* 1999; 82:589–596.

44. Odongo NE, Bagg R, Vessie G, Dick P, Or-Rashid MM, Hook SE, Gray JT, Kebreab E, France J, McBride BW. Long-term effects of feeding monensin on methane production in lactating dairy cows. *J Dairy Sci* 2007; 90:1781–1788, 112:107–130.

45. Oltjen JW, Beckett JL. Role of ruminant livestock in sustainable agricultural systems. *J Anim Sci* 1996; 74:1406–1409.

46. Overton TR, Waldron MR. Nutritional management of transition dairy cows: Strategies to optimize metabolic health. *J Dairy Sci* 2004; 87(E Suppl.):E105–E119.
47. Owens FN, Secrist DS, Hill WJ, Gill DR. Acidosis in cattle: A review. *J Anim Sci* 1998; 76:275–286.
48. Raeth-Knight M, Chester-Jones H, Hayes S, Linn J, Larson R, Ziegler D, Ziegler B, Broadwater N. Impact of conventional or intensive milk replacer programs on Holstein heifer performance through six months of age and during first lactation. *J Dairy Sci* 2009; 92:799–809.
49. Robison JD, Stott GH, DeNise SK. Effects of passive immunity on growth and survival in the dairy heifer. *J Dairy Sci* 1988; 71:1283–1287.
50. Roche JF. The effect of nutritional management of the dairy cow on reproductive efficiency. *Anim Reprod Sci* 2006; 96:282–296.
51. Schils RLM, Olesen JE, del Prado A, Soussana JF. A review of farm level modeling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. *Livest Sci* 2007; 112:240–251.
52. St-Pierre NR, Cobanov B, Schnitkey G. Economic losses from heat stress by US livestock industries. *J Dairy Sci* 2003; 86(E Suppl.):E52–E77.
53. St-Pierre NR, Thraen CS. Animal grouping strategies, sources of variation, and economic factors affecting nutrient balance on dairy farms. *J Anim Sci* 1999; 77:72–83.
54. Tedeschi LO, Fox DG, Tylutki TT. Potential environmental benefits of ionophores in ruminant. *J Environ Qual* 2003; 32:1591–1602.
55. Tylutki TP, Fox DG, Durbal VM, Tedeschi LO, Russell JB, Van Amburgh ME, Overton TR, Chase LE, Pell AN. Cornell net carbohydrate and protein system: A model for precision feeding of dairy cattle. *Anim Feed Sci Technol* 2008; 143:174–202.
56. USDA. Dairy 2007, part I: Reference of dairy cattle health and management practices in the United States, 2007. #N480.1007. USDA-APHIS-VS, CEAH, Fort Collins, CO. 2007.
57. Van Amburgh ME, Galton DM, Bauman DE, Everett RW, Fox DG, Chase LE, Erb HN. Effects of three prepubertal body growth rates on performance of Holstein heifers during first lactation. *J Dairy Sci* 1998; 81:527–538.
58. VandeHaar MJ. Efficiency of nutrient use and relationship to profitability on dairy farms. *J Dairy Sci* 1998; 81:272–282.
59. VandeHaar MJ, St-Pierre N. Major advances in nutrition: Relevance to the sustainability of the dairy industry. *J Dairy Sci* 2006; 89:1280–1291.
60. Wang SJ, Fox DG, Cherney DJR, Chase LE, Tedeschi LO. Whole-herd optimization with the Cornell net carbohydrate and protein system. II. Allocating homegrown feeds across the herd for optimum nutrient use. *J Dairy Sci* 2000; 83:2149–2159.
61. Warnick LD, Janssen D, Guard CL, Gröhn YT. The effect of lameness on milk production in dairy cows. *J Dairy Sci* 2001; 84:1988–1997.
62. Weigel KA. Exploring the role of sexed semen in dairy production systems. *J Dairy Sci* 2004; 87(E Suppl.):E120–E130.