Short Review of 30 Years of Advances in Dairy Cattle Nutrition

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Summary

Milk production per cow has increased markedly over the past 30 years. One reason for this increase is improved nutrition of cows. Better vitamin and mineral nutrition has reduced the prevalence of many health issues and has led to increased emphasis on the use of nutrition to improve animal health, not just milk production. About 50% of the cost of feeding a lactating cow is for energy, and we have greatly improved our understanding of energy metabolism over the past 3 decades. This has led to the formulation of more efficient diets. Feed is the major variable cost of producing milk, and we have improved our ability to compare the economic value of different feeds. Greatly increased computing power has allowed us to develop much more sophisticated ration evaluation and formulation software, which has increased our ability to formulate better diets and to better predict animal performance. However, additional improvements are always needed, and this will require research and new software to allow nutritionists to incorporate animal and diet composition variation into their formulation goals. Protein is the second largest contributor to feed costs. We have gone from CP to metabolizable protein (**MP**) to amino acids. This change has generally led to lower cost diets, while often increasing milk protein yields. Although much has been learned about dairy nutrition and much of what we have learned has been applied on-farm, continued progress is needed to keep the dairy industry as a competitive contributor to the human food supply.

Introduction

Based on USDA statistics, annual milk production has increased about 8700 lb/cow over the last 30 years. This increase occurred because improved nutrition, facilities and cow management allowed producers to capture a portion of the consistently increasing genetic potential of cows. This paper will discuss some of the major nutritional advances that contributed to increased milk yields and improved cow health. The list is not exhaustive and is clearly biased toward areas of interest to me. This paper is neither a scientific review (citations are limited) nor a detailed discussion of experimental data and recommendations. More detailed information regarding historical changes that have occurred in all areas of dairy science and the dairy industry can be found in the American Dairy Science Association Foundation Collection of 100-Year Reviews (ADSA, 2017).

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The major advancements that will be discussed are:

1. Vitamin and mineral nutrition
    - Use of minerals and vitamin to enhance immunity and improve animal health
    - Use of absorbed rather than total minerals in diet formulation
    - Use of organic trace minerals
2. Feed and diet evaluation and formulation
    - Estimating feed and diet energy values
    - Comparing economic value based on nutrient prices
    - Understanding and incorporating feed and animal variation
3. Protein nutrition
    - Development and application of metabolizable protein (**MP**) system
    - Formulating for specific amino acids

The Tristate universities have had major impacts in the areas of feed intake and dietary fat supplementation. Mike Allen's group at Michigan State has been at the forefront in feed intake regulation by cows culminating in the Hepatic Oxidation Theory (**HOT**). In addition, they have developed practical feeding recommendations based on HOT to optimize milk yields and body condition. Don Palmquist at Ohio State was a pioneer in fat nutrition of dairy cows. His research greatly increased our understanding of fat metabolism by ruminants and with Tom Jenkins developed what I think was the first commercial rumen inert fat supplement (calcium soaps). This product is fed throughout the world. Adam Lock's group at Michigan State is continuing to increase our understanding of fat nutrition and proper formulation strategies on how to best use fat supplements. Although these are important topics, I will leave it to those investigators to discuss.

Mineral and Vitamin Nutrition of Cows

Thirty years ago, the NRC (1989) listed requirements or recommendations for 7 macrominerals (needed in grams per day amounts), 7 trace minerals (needed in milligram per day amounts) and 3 fat soluble vitamins (A, D, and E). Many of these recommendations were mostly educated guesses based on little controlled research. Furthermore, with the exception of calcium and phosphorus, recommendations were mostly on a dietary concentration basis (not amounts per day) and were usually chosen because those concentrations usually prevented clinical deficiency diseases. A little more than 30 years ago, supplemental Se was shown to reduce the prevalence of retained placenta and the first paper showing that supplemental vitamin E and Se reduced the prevalence and severity of mastitis had been published (Harrison, et al., 1984; Smith, et al., 1984). The reduction in mastitis occurred with additional Se and vitamin E, even though cows and their calves displayed no classical signs of deficiency. This discovery led to research on how supplementation with other trace nutrients, mostly vitamin A, β-carotene, copper and zinc, could reduce mastitis and improve overall health. The vitamin E recommendations put out by NRC (2001) were based not on prevention of white muscle disease but rather on its ability to reduce mastitis. This was the first time to my knowledge that a mineral or vitamin requirement or recommendation was based on general health. Animal health is now considered when establishing NRC requirements for minerals and vitamins. This has led to improved animal health, but it also often has led to substantial over supplementation of some minerals and vitamins.

For several decades, the requirements for Ca and P were based on the factorial system (requirements for maintenance, lactation, pregnancy, and growth) and used an assumed absorption coefficient (**AC**) applied to the entire diet. For example, the NRC (1989) assumed that 38% of dietary Ca and 50% of dietary P was absorbed. Absorption coefficients were not used for any other mineral. In NRC (2001), the factorial approach was used to establish requirements for all minerals except cobalt, iodine, Se, and sulfur. Cobalt and sulfur are largely a bacterial requirement and expressing those requirements as a concentration of dietary DM make sense. Selenium supplementation is regulated and the requirements basically restated the Federal regulation (i.e., 0.3 mg of supplemental Se/kg of diet). Inadequate data were available on iodine to do little more than recommend a dietary amount that should prevent deficiency.

For the other minerals, requirements for the various physiological functions were established on an absorbed basis and then an AC calculated for the diet was used to derive a requirement for the dietary mineral. This system assigned AC to ingredients, rather than to the diet. However, in general, all basal ingredients (e.g., corn, alfalfa, soybean meal, etc.) had the same AC, but the AC for supplemental sources (e.g., copper sulfate, copper oxide, etc.) of minerals varied. This allowed more fine-tuning of mineral supplementation. The major issues with this approach was the limited data on AC for many minerals and the difficulty in determining maintenance requirements. The limited AC data for trace minerals is especially problematic because the AC are generally extremely small, often less than 5%. This means that you are dividing absorbed requirement by a small number and small changes in the AC can cause very large changes in dietary requirements. This was evident in the NRC (2001) manganese requirement. The AC for Mn for most diets (NRC, 2001) was approximately 0.85%. When this was applied to absorbed requirements, dietary concentrations of about 15 mg Mn/kg diet DM met requirements. Based on data published after 2001, diets with 15 mg Mn/kg would often cause clinical Mn deficiency. It is much easier to search the scientific literature now than it was in 2000 and data from studies not used by NRC (2001) show that Mn absorption probably is closer to 0.4%. When an AC of 0.4% is used, the dietary Mn requirement is about 32 mg/kg, which is likely adequate for most situations. A substantially increased database (compared with what was available for NRC, 2001) allowed a re-evaluation of the AC for magnesium sources and these revised AC are substantially different from the values in NRC (2001).

The factorial approach also does not account for everything minerals can do. For example, increased supplementation of some trace minerals has been shown to enhance immune cell function. In theory, this requirement should be a component of maintenance, but we do not know if immune function enhancement is captured with the factorial system. Sodium and potassium buffers and to a lesser extent some inorganic forms of magnesium have effects within the rumen (e.g., help maintain proper rumen pH), but these effects are not captured by the factorial system. Data accumulated through numerous studies have allowed the development of relationships between measurements such as milk fat yield, DM intake, and digestibility and dietary cation anion difference (**DCAD**). These relationships, along with factorial requirements, can be used to optimize supplementation of these minerals.

Over the last 30 years, several companies have developed various types of organic trace minerals. These compounds are usually metals (copper, zinc, and manganese) that have been complexed with an organic moiety, such as an amino acid or a sugar. A primary reason these products were developed was because they were thought to have greater bioavailability (a greater AC). Processes and interactions occurring within the rumen often reduce the AC of trace minerals. Organic minerals were developed to help prevent or lessen the antagonism that can occur in the rumen, thereby improving intestinal absorption of the metal. Often, but not always, organic Cu has a greater AC than copper sulfate based on the liver Cu bioassay. For other metals, we do not have good measures of relative absorption, so it is difficult to say whether absorption differs between sources. Nonetheless, several studies have shown that various clinical (immune function, SCC, hoof health, etc.) or production responses are often (but again, not always) improved when organic trace minerals are supplemented. Because we do not have good absorption data for these products, the absorbed mineral factorial approach used by most ration formulation software may not value these products correctly. We also are lacking good data that describes potential modes of action for organic trace minerals.

Over the past 30 years, we have gained substantial knowledge on many of the essential minerals. We have shifted from the concept that mineral adequacy was defined by the prevention of clinical deficiency and are now considering overall health of the animal. Increased emphasis needs to be placed on mineral excretion via manure because of environmental concerns. This means that bioavailability will become even more important and additional fine tuning of requirements is needed so we can reduce the degree of overfeeding minerals that is common today.

Compared with minerals, we have learned less about vitamin nutrition. Recommended supplementation rates for vitamins A and E have increased over the last 30 years, mostly because of the data showing positive effects on mammary gland health. Because of the substantial decrease in plasma tocopherol (vitamin E) and retinol (vitamin A) that occurs about 1 week prepartum, recommended supplementation rates have increased for prefresh cows. For most of the past 30 years, very little research was conducted with vitamin D and essentially the only factor considered when developing recommendations was calcium metabolism. Recently, studies have shown that vitamin D can have profound effects on immune function, and those responses occur at supplementation rates greater than what is needed to optimize Ca metabolism. Based on limited data, plasma threshold values for 25-OH vitamin D have been established so that we can titrate optimal supplementation rates. I expect that research on vitamin D will continue to be an active area of study. Thirty years ago, the only water soluble vitamin that was commonly supplemented was niacin. Since then, research has shown positive effects of supplemental biotin on hoof health and milk production, and it has become a common component in diets. Choline, in rumen protected forms, was shown to improve transition cow health and increased milk production in early lactation. Other water soluble vitamins, notably folic acid, B_{12}, and vitamin C, have received research attention. Production often was increased with folic acid and B_{12} supplementation; however, they are not commonly fed, likely because of economics. Many B-vitamins are extensively metabolized in the rumen and rumen protected forms of some vitamins are available. Whether supplementation with these products is profitable has yet to be definitely determined.

Feed and Diet Evaluation and Formulation

Arguably, this is the area of dairy cattle nutrition that has changed the most in the last 30 years. The increased power and decreased cost of personal computers has allowed us to develop more complex formulation software. We have gone from balancing for a few nutrients (CP,

NE_L, fiber, Ca, and P) to using complex supply models and formulating for dozens of nutrients. The development of a robust commercial feed testing system went hand-in-hand with the increasing complexity of nutritional models. Commercial labs now routinely analyze for components that previously could only be done by university research labs. For example, most labs can now measure in vitro digestibility of neutral detergent fiber (**IVNDFD**). This can be useful in estimating energy, DM intake and overall characterization of forages. Some labs can measure in situ disappearance of CP which is needed to estimate rumen degradable and undegradable protein. Commercial labs are actively developing new assays, indices, and equations to better characterize feeds and diets.

Estimating energy values

Feed and diet energy estimation has changed markedly over the past 30 years. Thirty years ago, energy values (either NE_L or TDN) of concentrate feeds, such as corn, distiller grains, and soybean meal, were considered constants and values from standard feed composition tables were used. Many of those values were derived from digestibility trials using sheep that were fed single component diets (e.g., all corn grain). Energy values of some forages were also considered constants, but some labs estimated energy values for common forages using a simple regression equation based on ADF. These equations did not account for substantial sources of variation that are known to affect the digestible energy (**DE**) concentration and they were forage specific (equations were available for corn silage, grass, and alfalfa).

Over the past few decades, more complex equations and models were developed to estimate DE or TDN and some of these were quickly adopted by commercial labs because the labs had the ability to measure the necessary inputs. The OSU equation (Conrad, et al., 1984; Weiss, et al., 1992) was one of the first equations that attempted to incorporate most factors that were known to influence DE or TDN and included estimated digestible protein, digestible fat, digestible NDF (estimated using lignin) and digestible nonfiber carbohydrate (**NFC**). This equation has been modified several times and now includes digestible starch and digestible residual organic matter (ROM = NFC – starch) (Weiss and Tebbe, 2018) and estimates DE rather than TDN. As the ability of commercial labs to measure in vitro NDF digestibility expanded, that value could be used in the OSU equation to estimate NDF digestibility. Equations that account for the effect of DM intake on digestibility and the effect of starch on fiber digestibility can be combined with the OSU equation to estimate DE when cows are fed mixed diets at productive levels of intake.

An alternative approach to using simple feed composition inputs (e.g., CP, ash, NDF, starch, and fatty acids) to estimate DE supply was to partition carbohydrate and protein fractions into different kinetic pools and use digestion rates and rates of passage (e.g., Cornell Net Carbohydrate Protein System). Both methods have advantages and disadvantages, but both are a vast improvement over using constants or ADF-estimated values to describe the energy content of feeds and diets. Progress has also been made in estimating ME. ME is measured as DE minus energy lost in urine and via methane. A regression equation developed at the USDA center in Beltsville, MD from dairy cow experiments has been used for decades to estimate ME. The only variable in that equation was dietary DE concentration. In NRC (2001), a small adjustment for dietary fat was made to the standard equation. Over the range of diet DE concentrations that would be commonly fed to lactating cows, the efficiency of converting DE to estimated ME would vary only from about 0.84 to 0.86. That range is less than what would be expected across diets. Because the standard equation did not include dietary CP concentration, urinary energy loss was underestimated with high CP diets. Increased concentration of digestible fiber increases methane losses but that also was not included in the standard equation. We now are better at estimating urinary N losses and converting that into estimated urinary energy, and we have equations to estimate methane using concentrations of digestible fiber and dietary fat. These equations in concert with improved estimated of DE have increased the accuracy of estimating dietary ME. However, most software formulates diets for NE_L, which is ME minus the heat increment of the diet. We have made almost no advancements in improving our estimates of heat increment and most software uses either a constant or an old simple regression equation to convert dietary ME to NE_L. We need to either improve our ability to estimate NE_L or just formulate for ME, which is essentially what we do now since the efficiency of converting ME to estimate NE_L is almost a constant.

Economic evaluation of feeds

Because feed is the largest single variable cost of producing milk, increasing income over feed costs (**IOFC**) is a goal of most nutritionists. One way to increase IOFC is to use cheap feeds. However, determining whether a feed is a good buy cannot be done simply by comparing prices per ton of ingredient. More than 80 years ago, a mathematical method was developed by J. Petersen to compare values of different feeds based on their energy and protein concentrations and using corn (energy) and soybean meal (protein) as the reference feeds. A major problem with this method was that everything was relative to corn and soybean meal. In addition, it only valued energy and protein. About 50 years ago, linear programing was used in least-cost diet formulation software. Least-cost formulation often does not result in maximum IOFC because the cheapest diet may reduce milk yields; however, it can be used to compare economic value of different feeds. Using least cost formulation to make ingredient purchasing decisions was cumbersome (numerous diets had to be formulated) and it was situation specific (e.g., an ingredient may be a good buy but only if other ingredients were available at a certain price to compliment the feed). About 20 years ago, a new method was developed by Normand St-Pierre (St-Pierre and Glamocic, 2000), which used prices of numerous feeds in a given market. Using a statistical technique similar to multiple regression with prices as the dependent variable and nutrient composition (e.g., metabolizable protein, energy, effective fiber, and non-effective fiber) as independent variables, the prices of individual nutrients could be estimated. For example, in a given market 1 Mcal of NE_L might be worth on average $0.05 and 1 lb of MP might be worth on average $0.45, regardless of the source of the nutrient. Using this method, the nutrient value of a feed could be calculated (i.e., the sum of the value of the nutrients the feed contained) and compared to the market price. If the market price was greater than nutrient value, a nutritionist might try to remove the feed from the diet, and if the market price was lower than the nutrient value, the nutritionist might try to increase inclusion rates.

This approach works well in many situations, but it is based on the premises that nutrient descriptions of feeds explain all their value. For forages and some concentrates, this is not the case. Haycrop forages with high concentrations of fiber have lower energy concentrations and often lower protein concentrations so that their nutrient value is usually less than better quality forages. However, because lower quality forages often reduce DM intake and milk yield, they are worth even less. Research done at Michigan State in Mike Allen's lab relating IVNDFD to intake and milk yield (e.g., (Oba and Allen, 1999) offered a solution and we now have methods to adjust the nutrient value of forages based on IVNDFD (Weiss and Tebbe, 2021).

Incorporating diet and cow variation into dairy nutrition

Although we have always known that the nutrient composition of feeds varied, for most of the past 30 years, we have used a combination of data from feed composition tables (i.e., a constant) and data from a single sample we sent to a lab when formulating diets. The numbers in feed tables could be a mean from a large number of samples or it could have been from a single analysis. When we sampled feeds and obtained lab data, we usually assumed the sample perfectly represented the feed until it was time to sample again and then we assumed the new data perfectly represented what we were feeding. Many feed composition tables now include not only the mean concentration but also the number of samples that were used to derive the mean and the standard deviation (**SD**) associated with the mean. Many labs have now started to collate data within a farm and report not only the data for the sample but also the SD and a rolling mean for the farm. To use the SD properly in ration formulation and feed purchasing decisions, the sources of the variation must be known. We have partitioned variation in nutrient composition within feeds and TMR into sampling variation, analytical variation and real variation (St-Pierre and Weiss, 2015). If sampling variation is high, this means you need to improve your sampling techniques or take more samples and average the values to get a number that more accurately reflects the feed. If analytical variation is high, you should consider finding a new lab. If real variation is high, then you need to consider adjusting diet formulation strategies. Reducing the inclusion rate of highly variable feeds usually increases the consistency of the TMR. The safety factor applied to nutrients (i.e., the degree of over supplying a specific nutrient) should be greater when using highly variable feeds than when using consistent feeds. However, increasing the safety factor because of high variability should only be done if it is real variation. Increasing the safety factor if sampling error is the reason for the high variation usually reduces IOFC and often does not reduce the risk of underfeeding a nutrient. At this time, the adjustments many nutritionists make for highly variable feeds is qualitative. However, as computing power continues to increase (and computing costs decrease), diet formulation may incorporate variation into the calculations. This is called stochastic formulation and is used by some nutritionists in the poultry industry. With this system, we would not formulate to a specific value, rather we base formulation goals on probabilities. For example, a diet might be formulated to contain at least 16% CP, 80% of the time. This approach incorporates risk into formulation strategies and should ultimately result in less expensive and safer diets.

The next step is to incorporate animal variation into our formulation systems. At best, current requirements represent averages. For example, an average 1450 lb cow producing 85 lb of milk may need 45 g/day of sulfur to meet her requirement. However, not all 1450 lb cows producing 85 lb of milk need 45 g/day of sulfur. Some cows will need more and other less. The U.S. recommended daily allowance (**RDA**) system used for humans essentially increases the average requirement for most nutrients by 20% to get the RDA. The 20% excess is supposed to equal 2 SD units. Increasing the RDA by 2 SD above the average requirement will meet the requirement for a nutrient for 98% of the population; whereas, the average requirement only meets the requirement for

50% of the population. This is one, albeit somewhat arbitrary, approach to incorporating animal variation into formulation. However, the major source of variation in requirements is likely not among similar animals but among dissimilar animals within a pen. For a one group TMR system, the range in milk yields per cow within a pen could easily be more than 100 lb/day. In addition to variation in milk yields and composition, stage of gestation and lactation and body weight will also vary. Formulating a diet to meet requirements for the average cow in a pen will not provide adequate nutrition for high producing cows and will result in lower milk yields. Conversely, formulating a diet to meet the needs of the highest producing cows in the pen will result in excessive feed costs because most of the cows in the pen will be overfed. Limited research has been conducted to determine the economically optimal formulation specifications for groups of cows. Depending on the relative cost of milk and feed, formulating a diet to meet the MP requirements for pen average milk production plus 1 to 1.5 SD units usually has been economically optimal. This approach was not widely applied because for most farms, the SD in milk yield among cows was not known because individual cow milk yields could not be measured on farm. As technology has improved, the cost of measuring individual milk yields has dropped and it is becoming more common. Other technology is being developed that permits numerous measures from individual cows, such as rumination time, rumen pH, and milk composition. We need to learn how to best use this information to improve efficiency and cow health.

Protein Nutrition

Over the past 30 years, we have almost completely shifted away from CP and now formulate diets for MP. To do this, we needed to develop methods to analyze feeds for rumen degradable (**RDP**) and undegradable protein (**RUP**) and we needed to developed models that could convert those fractions into MP. Measuring protein fractions is still problematic, which causes many nutritionists to rely on table values for RDP and RUP. However, even with the analytical limitations, the MP system has proven superior to the CP system for formulating diets. About 20 to 25 years ago, researchers started to evaluate whether amino acid composition of the MP affected milk and milk protein yields. Initially, nutritionists simply used protein sources that were high in lysine (e.g., blood meal) or methionine (e.g., fish meal) because we thought those 2 amino acids were likely most limiting. Years of research were conducted to quantify both supply of metabolizable amino acids and responses to change in supply. A typical experiment consisted of infusing various amounts of different amino acids into the abomasum or duodenum and measuring change in milk protein yields. Most of the research was on lysine and methionine, but within the past 5 to 10 years, histidine has received increasing interest. Dietary guidelines for methionine and lysine supply were made by NRC (2001) and others, but these were not actual requirements or response functions. Most commonly, guidelines for lysine and methionine were expressed as a percentage of estimated MP; whereas, requirements and response function should be expressed as grams per day of metabolizable methionine and lysine (or any other amino acid). We are now developing actual responses surfaces for various amino acids and future formulation software will likely include equations for many amino acids.

Formulation based on amino acids rather than MP, if done correctly, should allow more nitrogen efficient diets. We should be able to obtain equal or greater yields of milk protein, while cows are consuming less nitrogen (i.e., CP). However, care needs to be exercised when decreasing CP because protein does more than just provide amino acids. Increasing concentration of CP can increase digestibility of fiber and dry matter (Lee, et al., 2012), thereby increasing the energy concentration in the diet and it can increase DM intake. Research is needed to determine the right combination of amino acid balancing with providing enough CP so that nitrogen efficiency is high but cows also maintain high levels of production of milk and all milk components.

At least 2 issues remain with respect to amino acid nutrition. First, our estimates of supply of metabolizable amino acids need work. Currently, we estimate RUP of feeds and then usually assume the amino acid composition of the feed (which is usually based on table values) is the same as the amino acid profile of the RUP fraction. In addition, the digestibility of all amino acids in the RUP fraction are assumed to be the same and equal to the digestibility of the total nitrogen in the RUP fraction. We also assume the amino acid profile of microbial protein is constant. Measuring supply of metabolizable amino acids is becoming exceedingly difficult because of the need to use intestinally cannulated cows, and the concerns about animal welfare will greatly limit the availability of cannulated animals. Progress in this area may be limited.

The other issue is that requirement models currently only consider amino acids as building blocks of protein, which is why milk protein yield is the common response variable. However, amino acids also have regulatory and metabolic functions and can affect numerous physiological functions independent of being a precursor for protein synthesis. For example, research mostly from the University of Illinois (e.g., (Vailati-Riboni, et al., 2017) has shown that supplementing rumen protected methionine to prefresh cows can improve immune function, cow and calf health and alters expression of numerous genes. Developing equations to estimate these responses will be difficult and formulation models may have to treat this aspect of amino acid nutrition as an add-on to the amounts needed to meet protein synthesis needs.

Where Do We Go From Here?

Dairy nutrition is a maturing science, which means we should not expect revolutionary changes in the way we feed cows. However, this does not mean we do not have a lot yet to learn and apply. We need to continue to determine how we can use nutrition to improve the health and welfare of cows. This may mean different supplementation strategies for vitamins and minerals or it could mean evaluating how other nutrients affect immune function and cow health. We now have technology that allows cows to be housed in groups but evaluated and even managed as individuals. We need to learn how best to use the vast amount of data that we can collect on cows to formulate cost effective and efficient diets. Continued emphasis is needed on developing diets that use human food byproducts effectively. Ruminants have the ability of increasing the human food supply without directly competing for nutrients. More research is needed to develop efficient feeding systems that produce more desirable dairy products. This could be enriching milk with specific vitamins and minerals, altering milk fatty acid profile, or changing milk protein characteristics. Lastly, we need to continue to develop better ways to convert research information into on-farm application.

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