

Review

# Environmental and Economic Responses to Precision Feed Management in Dairy Cattle Diets

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**Abstract:** The dairy industry is under pressure to reduce its environmental impact while producing more milk to meet society's needs. Precision feed management (PFM) is one tool that can be used to meet this challenge. A simple definition of PFM is to provide adequate, but not excessive, nutrients to meet animal requirements. There has been an industry trend to decrease diet nitrogen (N) and phosphorus (P) in the last 20 years. New York herds lowered diet N by 10.8% between 1999 and 2019. Milk per cow increased by 40% during this time, while total manure N excretion decreased by 8.1%. Research results from on-farm trials have consistently indicated that lowering diet crude protein (CP) decreases manure N excretion while improving profitability; in a 3-year study with 8 herds, diet CP was decreased by 9.7%, while manure N excretion was 14% lower. Income over purchased feed cost increased by \$137/cow/year. Carbon footprint (CF) has also decreased. A decrease of 19% between 2007 and 2017 was reported for the United States dairy industry. The dairy industry has already made significant strides in improving milk production while lowering its impact on the environment; however, there are additional opportunities to further reduce nutrient excretion and emissions into the environment and increase the efficiency of nutrient use.

**Keywords:** nitrogen; phosphorus; ammonia; methane; grouping; carbon footprint; sustainability



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## 1. Introduction

The dairy industry is under continuing pressure to improve efficiency, sustainability, and lower its environmental impact. At the same time, demand for milk and milk products are expected to increase. The world population is projected to increase to 9.7 billion by 2050 [1]. Agricultural food production needs to increase by 50 to 70% to meet the needs of this expanded population. Per capita milk consumption is projected to increase by 16% by 2030 [2]. Global milk production needs to increase by 35% by 2030 to meet this demand. A second paper projected that the demand for dairy products in 2050 will be double the demand in 2000 [3]. The increased demand projections are a combination of two factors: One is the increase in population. The second factor is the increased consumption of cheese, yogurt, ice cream and other dairy products as the economic status of families improves.

Milk and dairy products are high-quality sources of nutrients. Milk provides 13 essential nutrients required in human diets. These include protein, calcium, iodine, and B-vitamins. Animal proteins have been reported to have a bioavailability 1.4 times greater than plant protein sources [4]. Protein quality and the upgrading of plant amino acids by dairy cattle also needs to be considered when evaluating the importance of milk and dairy products in human diets [5,6]. A recent paper reported that one-half of the total protein supply needs to be from animal-based proteins to meet nutrient requirement recommendations [7]. Animal proteins are also needed to provide required nutrients at a minimum cost [8]. The value of milk and dairy products in the diets of different age groups has been reviewed [9]. It is also important to recognize that livestock have social and economic roles in developing countries [10].

Precision feed management (PFM) is one tool that the dairy industry can use to address concerns about environmental impact. The simple definition of PFM is to provide adequate, but not excess nutrients, to support animal health and productivity. In New York, there is a PFM work group. This includes university faculty, cooperative extension employees, representatives of regulatory agencies, nutrition consultants and feed industry personnel. This group has expanded the PFM definition to include forage system management. The current definition of PFM used in New York is “The continual process of providing adequate, but not excess, nutrients to the animal and deriving a majority of the nutrients from the homegrown feeds through the integration of feeding and crop management for the purpose of maintaining farm environmental and economic sustainability.” The PFM work group has developed benchmark guidelines used in evaluating dairy diets. These include forage neutral detergent fiber (NDF) intake  $\geq 0.9\%$  of body weight, ration phosphorus (P)  $< 110\%$  of requirements, diet crude protein (CP)  $< 16.5\%$  and milk urea nitrogen (MUN) of 8–12 mg/dL. A key concern in the United States is to manage farm nutrients to minimize manure nutrients leaving the farm and impairing water quality on a watershed basis [11]. A trial was conducted comparing a control total mixed ration (TMR) with a treatment group in which the total mixed ration (TMR) was adjusted weekly for each individual cow [12]. There were significant increases in milk, energy-corrected milk (ECM) and feed efficiency for cows in the treatment group. Precision feed management can improve the efficiency of producing milk [13]. An overview of the role of precision dairy farming in the Australasia region is available [14]. This group defined some focus areas needed to increase the use and adoption of precision dairy farming. These include better industry coordination and leadership, defining the value of precision dairying, increasing technology available to farms, and providing educational and training opportunities for dairy producers.

Whole farm nutrient management (WFNM) plans are an integral component of a comprehensive PFM program. These plans are targeted to minimize nutrient excretion to the environment. A key concern is the impact of excess nutrients on water quality [15]. In the United States, these plans are a combination of federal and state regulations. These plans include an inventory of all nutrient sources on the farm, nutrient imports, nutrient exports, determination of crop nutrient needs based on soil test results, and crop yields to supply nutrients to minimize environmental impact while maximizing the agronomic benefits. Plans are developed by a certified nutrient management planner and detailed farm records need to be maintained to verify compliance. Herds are audited to verify compliance. The steps on developing nutrient management plans have been outlined [16,17].

The aim of this review is to present and describe successful on-farm precision feed management research, highlighting the importance of adequate diet balancing and the issues regarding optimal N and P diet provision and their impact in environmental and economic responses.

## 2. Nitrogen and Ammonia

Nitrogen (N) is an environmental concern for both water and air quality. Excess N intake is expensive and lowers the efficiency of converting intake N into milk. Ruminants can convert simple N sources, such as urea, into high-quality amino acids [18]. In addition, ruminants can also recycle N within the animal [19–21]. Dairy cows can also convert low-quality human-inedible proteins into high-quality edible protein (HEP) for use in human diets [22,23]. A study in Sweden replaced cereal grains and soybean meal with co-product feeds including beet pulp, distiller’s grain, and rapeseed meal [24]. Cows fed the co-product diets produced 2.56 to 2.68 times more HEP than consumed. The next step is to include human-digestible amino acids in the calculation [5,6].

Nitrogen-use efficiency (NUE), milk nitrogen efficiency (MNE), and efficiency of nitrogen use (ENU) are the common metrics used to assess the efficiency of N use [25–27]. This is calculated as the grams of N in the milk produced divided by the grams of dietary N intake. If dietary N intake is 730 g and milk N is 234 g, then  $NUE = 32\%$ . The range of NUE observed in commercial dairy herds is 20 to 40%. The theoretical maximum NUE

from research literature is 40–45%. The estimated MNE for 85 New York dairy farms in 2004 had an average of 28.8% with a range of 21.4 to 35.8 [28]. A recent paper surveyed 28 United States dairy farms and concluded that milk yield was optimized at a NUE of 34.7% [29]. This same study had data on 285 pens on these farms. The average pen NUE was 27.8% with a range of 14.2 to 46.7%. The relationship of NUE, milk production and profitability in eastern Canadian dairy herds was investigated [30]. Data were obtained from 100 herds and organized in clusters with NUE values of 22, 27, 30, and 36%. Diet CP decreased from 16 to 14.2% as NUE increased. This indicates an opportunity in dairy herds to improve efficiency of N use by the better balancing of diets. Milk and fat-corrected milk (FCM) production were significantly lower in the cluster herds with 22% NUE. Income over feed cost (IOFC) increased as NUE increased.

A classic trial examined diet CP and N flows in dairy cattle [31]. Diets fed ranged from 13.5 to 19.4% CP. Milk yield was not significantly different between the diets for cows producing 36 to 38 kg. Fecal N excretion was lower for a 15% CP diet but similar for the other diets. Urinary N (UN) excretion increased linearly as diet CP increased. The urinary urea N (UUN), as percent of UN, increased from 55.4% for a 13.5% CP diet to 81.8% for a 19.4% CP diet. The percent of N intake captured in milk protein decreased from 36.4% to 25.3% as diet CP increased from 13.5 to 19.4%. This indicates a lower efficiency of N use as N intake increased. Urinary urea N increased from 86 to 320 g/d as diet CP increased from 15 to 21% [32]. The increase in urinary N excretion and lower efficiency of N use has been reported in other papers [33–35]. A review paper reported that decreasing diet CP from 20 to 15% reduced annual fecal N excretion by 21% and urine N by 66% [36]. Rumen N metabolism and the relationships to N excretion papers are available [37–39].

The importance and use of amino acids has been described [39–41]. The effect of postruminal infusion of casein was reported [42]. Milk production was 1–4 kg/d higher, and there was a 10–15% increase in milk protein yield when casein was administered. These results indicate a potential benefit to amino acid supplementation. A multi-university study using rumen-protected methionine and lysine in diets based on corn silage and corn grain was reported [43]. The protein sources used were soybean meal or corn gluten meal and urea. Milk protein yield and milk production were higher on the corn gluten meal diets when the rumen protected amino acids (RPAA) were supplemented. Milk yield was not improved for cows fed soybean meal when RPAA were added. A second paper [44] followed the same experimental design. Added RPAA did not increase milk production or milk protein yield in cows fed soybean meal. Milk and milk protein yields were higher when rumen-protected amino acids were supplemented to the corn gluten meal diet. There have been several meta-analysis papers published when rumen-protected methionine (RPM) was used [45–47]. There was an increase of milk protein yield of 2.23 g of protein for each gram of MP methionine intake before the breakpoint [46]. A multiple regression analysis indicated that milk production and milk protein percent were significantly higher when RPM was fed [47]. Amino acids have also been reported to have benefits for reproduction, transition cow health and heat stress [48–51].

Milk urea nitrogen (MUN) is one tool that can be used at the farm level to assess the efficiency of diet N use [52–57]. MUN increased from 7.7 to 15.6 mg/dL as diet CP increased from 13.5 to 19.4% [31]. A second trial reported that MUN increased from 7.9 to 24.5 mg/dL as diet CP went from 15 to 21% CP (32). There is also a linear relationship between MUN and urinary N excretion [53,54]. UUN can also be predicted from MUN [32,52]. One equation was  $UUN \text{ g/d} = -48.6 + 16.2 \times MUN$  when MUN was between 5 and 16 mg/dL [52]. The current guideline for MUN in dairy herds in the New York PFM program is 8–12 mg/dL. Many U.S. dairy herds receive daily bulk tank MUN values from milk processors. This provides a tracking tool to flag changes that may have occurred in the forage or feeding program.

Ammonia emissions from dairy farms can have health implications for both animals and humans. The effect is due to the irritant effect of ammonia on the eyes and lungs. Ammonia is involved with the formation of fine particles (PM<sub>2.5</sub>) which are a risk for human health [58]. The relationship between diet CP and ammonia emissions has been

reported [59–63]. Ammonia emissions decreased by 66% on a diet with 14% CP compared to a 19% CP diet [60]. A second paper reported that a one-unit increase in diet CP resulted in an increase of 10.2 g/cow/day in NH<sub>3</sub> emissions [60]. The same paper indicated that NH<sub>3</sub> emission increased by 16.3 g/cow/day when dry matter intake (DMI) increased by one unit. Manure ammonia emissions were higher as diet CP increased [64,65]. Diets with higher levels of fermentable carbohydrates were reported to lower rumen NH<sub>3</sub> production [66]. The relationships of diet and management factors on ammonia emissions have been summarized [67–69]. A review paper on ammonia emissions for dairy cattle is available [70].

### 3. Phosphorus

Phosphorus is an environmental concern for water quality. Excess diet P increases P excretion, which can result in higher soil P levels and an increased risk of P leaching to water supplies. There can also be P in manure runoff, which can cause eutrophication and algae growth in surface waters. An additional concern is a potential shortage of mineral P sources in the future. There is an increase in both total and water-soluble P content of manure when cows are fed P above requirements [71]. This increase in P content of manure would require more hectares of land to apply manure based on nutrient management guidelines. One reason for feeding excess P in dairy herds has been a perception that higher diet P levels improve reproduction. A second reason is to provide a safety factor in diet formulation to assure that P requirements are met. A review paper reported that surveys in the United States in the 1990's found that diet P levels were often 25% above requirements [72].

There have been numerous research trials examining the relationships between milk production and reproductive performance, and diet P. A two-lactation trial reported that a diet P level of 0.28% was adequate for cows producing 9000 kg of milk [73,74]. Two trials using diet P levels of 0.31, 0.40 and 0.49% were conducted by the same group [75]. Fecal P increased as diet P increased. A reduction of fecal P excretion of 23% was observed when diet P decreased from 0.49 to 0.40%. There was no difference in milk production between the three diet P levels for cows producing 11,000 kg of milk. A two-year trial with diet P of 0.38 and 0.48% reported no differences in milk production or reproduction between the diets [76]. The other trial had data from cows fed with 0.31, 0.40 and 0.49% diet P levels for 2 or 3 years [77]. The authors concluded that there was a decrease in bone P content but that this did not affect bone strength. Bone P content or strength was not affected in cows on a 0.39% P diet. Cows producing >11,900 kg may be borderline deficient when fed a 0.32% P diet. Reproduction was not reduced in these trials. A 2-year lactation trial was conducted with diet P levels of 0.35 and 0.42% [78]. There was no difference in milk production in cows averaging 36 kg of milk. Fecal P was significantly higher for cows fed the 0.42% P diet (0.84 versus 0.62%). A 4-year trial using diet P of 0.36 and 0.49% in the winter months was conducted [79,80]. In the summer months, diet P levels were 0.36 and 0.42%. No significant difference in milk production, milk composition or reproduction between the diets were detected in this study. The low P diet provided about 80% of the 1991 United Kingdom feeding standard.

No differences in reproductive performance were observed in cows fed diets with 0.37 or 0.57% P and producing 35 kg of milk [81,82]. There was no effect on estrus intensity or duration when diets with 0.38 or 0.48% P were fed [83]. No effect on ovarian activity, reproduction or milk production was detected in cows fed diets with 0.35 or 0.47% P [84]. Reducing diet P from 0.41 to 0.35% was estimated to save CAD 20/cow/year [85].

The trend in the United States is to feed lower P diets. One reason is that the research results described above provide confidence that feeding diet P close to requirements does not impair milk production or reproductive performance. A second reason is the increased use of nutrient management plans to comply with environmental regulations. An evaluation of changes in diet P in New York herds between 1999 and 2019 was conducted [86]. During this time, the number of cows decreased 10.5% while milk/cow increased by 40.4%.

Total New York milk production increased 26%. Diet P went down 18.8%, while manure P/cow/year was 9.2% lower. On a statewide basis, total manure P excretion decreased by 18.8%, and whole farm P mass balance was 51% lower. A similar analysis was done for the Vermont dairy industry [87]. Cow numbers dropped by 21%, and milk/cow increased by 26%. Total Vermont milk was 4.8% lower. Diet P decreased from 0.48 in 1999 to 0.39% in 2019. Total Vermont manure P excretion was 21% lower. These results indicate that lowering the overfeeding of dietary P can reduce the environmental impact of the dairy industry on a statewide basis.

#### 4. Methane

Methane (CH<sub>4</sub>) is a natural product of carbohydrate fermentation in the rumen. In 2020, methane accounted for 10.9% of all greenhouse gas emissions in the United States [88]. Agriculture accounted for 9.9% of all GHG emissions. Enteric methane was 2.9% of total GHG emissions, while enteric CH<sub>4</sub> from dairy cows was 0.73%.

Factors that determine the amount of methane produced in the rumen include DMI, milk production, forage type and quality, carbohydrate sources and processing method, fatty acid profile of fats, amount and ratio of the volatile fatty acids produced during fermentation and feed additive use [89]. Feed intake and the total quantity of carbohydrates digested in the rumen are key drivers of enteric CH<sub>4</sub> [90,91]. Mitigation strategies and the use of feed additives to alter methane emissions have been recently reviewed [92–96]. A meta-analysis of the impact of 3-nitrooxypropanol (3-NOP) on enteric CH<sub>4</sub> emissions was recently published [97]. Methane emissions were reduced by 30.9 to 32.7% in the diets when 3-NOP was added.

#### 5. On-Farm Research

A vital component of the PFM program is conducting on-farm research. This is essential before implementing research results. This is also a crucial step in model development as a beta test before making models available for use by nutrition consultants and feed companies for routine use in evaluating and formulating diets. There is also the value of on-farm demonstration research to instill confidence into nutritionists and dairy producers to adopt and utilize new concepts.

##### 5.1. Dairy Sustainability Trial

This was a project conducted on two dairy herds to assess tools and methods to develop a process to improve sustainability on dairy farms. This project was initiated in 1993 and included 16 Cornell faculty and 5 graduate students from 6 academic departments [98,99]. One herd was used over a 12-month period to evaluate a beta version of the Cornell Net Carbohydrate and Protein System (CNCPS) model on a commercial dairy herd [100]. This was done in cooperation with the feed company nutritionist working with the farm. The Cornell group formulated diets monthly for the high group. Diet CP was lowered from 20.3 to 18.3%, while diet MP increased from 2807 to 2971 g/day. The amount of alfalfa silage and high-moisture ear corn in the diet was increased. Diet levels of soybean meal and tallow were reduced, and a heat-treated soybean meal was added to the diet. Home-produced feeds increased from 56 to 63% of diet DM. Milk production increased from 43.4 to 46.5 kg. Diet feed cost went from USD 4.58 to USD 4.21/cow/day. Net farm income increased by USD 40,198 per year for this group. Total manure N was 34% lower, while manure ammonia N went down by 48%. The results of this trial confirmed that the CNCPS model can be used on commercial herds to lower CP, improve efficiency of N use, lower N excretion into the environment and improve profitability.

##### 5.2. Washington State Herd

A trial with three experiments was conducted on a dairy herd in the state of Washington [101]. The objective was to evaluate the use of high-quality rumen-undegraded protein (RUP) sources or rumen-protected amino acids (RPAA) on NUE and manure ammonia

emissions. Diets were formulated using the Agricultural Modeling and Training Systems Cattle Professional (AMTS) program [102]. This is a commercial program with a license for using CNCPS biology. Trial 1 and 2 used multiparous dairy cows while trial 3 used primiparous cows. A control diet and a diet balanced with methionine and lysine were formulated. Table 1 contains the results of this study. The authors concluded that feeding lower CP diets decreased manure N excretion and NH<sub>3</sub> emissions while increasing NUE.

**Table 1.** Diet Nutrient Content and Milk Production in a Washington State Dairy Herd <sup>a,b</sup>.

Item	Trial 1		Trial 2		Trial 3	
	Control	AA Balanced	Control	AA Balanced	Control	AA Balanced
Diet CP, %	17.9	17.2	17.8	15.5	16.7	15.5
MP Intake, g/cow/d	2641	2822	2740	2796	2130	1998
Methionine, % of MP	1.95	2.34	1.91	2.19	1.83	2.20
Lysine, % of MP	6.41	7.23	6.32	6.67	6.64	6.88
Milk Yield, kg/cow/d	43	44.9	44.3	43.7	31.3	31.3
NUE, %	34	35.9	33.3	35.6	32.2	34.9
Manure N, g/cow/d	459	437	476	408	362	322
IOFC (2014), \$/cow/d	15.16	15.24	14.99	13.98	11.09	11.27

<sup>a</sup> Adapted from Chen et al. [101]. <sup>b</sup> CP = Crude protein; MP = metabolizable protein; NUE = nitrogen-use efficiency; IOFC = income over feed cost (\$/cow/day).

### 5.3. Western New York Herds

Two dairy herds were used in an 8-month study to validate recent changes in the CNCPS model [103]. These changes increased the sensitivity of the model to N intake and adjusted the requirement calculations [104]. The CNCPS model was used to formulate diets monthly for the high group diet. The nutritionist working with each herd was involved in identifying potential diet adjustments in cooperation with the Cornell group. Table 2 contains the results of this study. In herd B, total diet forage had to be decreased due to a limited forage inventory. High-moisture corn, soyhulls and wheat middlings were increased to replace forage. Herd B also stopped using bovine somatotropin during the trial, which lowered milk production. Diet CP was lowered by 4.5 to 5.7% while MP was decreased in herd A, but MP increased in herd B. Feed cost was lower in the final diet in both herds. Income over feed cost and income over purchased feed cost increased in the final diet in both herds. The smaller increase in herd B was associated with the cost of replacing forage in the diet. Predicted daily manure N excretion decreased by 6 to 11.8%. These results indicate that diet CP can be decreased without impacting milk production. Nutrient excretion can be decreased and income over feed cost improved at the same time.

### 5.4. Whole-Farm Project

A project was conducted over a 5-year period to evaluate the impact of implementing nutrient management practices that integrate animals, crops, and manure management [105]. Diets were formulated using the CNCPS 5.0 model [106]. The total number of animals and cows milked increased during the trial. The portion of the diet from forage increased due to increased crop yields and decreased forage storage losses. Total manure excretion N and P decreased as did N and P per hectare. Table 3 summarizes the results of this study. The results of this study indicate that changes in farm management to reduce nutrient excretion can be made while improving farm profitability.

**Table 2.** Diet Nutrient Content, Milk Production and Income Over Feed Cost <sup>a,b</sup>.

Item	Herd A		Herd B	
	Initial Diet	Final Diet	Initial Diet	Final Diet
Diet CP, %	17.6	16.6	17.7	16.9
MP Intake, g/cow/d	2950	2769	2546	3090
Forage, % of Diet DM	54	57	60	48
Milk Yield, kg/cow/d	35.9	36.3	37.5	36.4
Feed Cost, \$/cow/d	4.07	3.35	4.37	4.12
Income Over Feed Cost, \$/cow/d	5.32	6.31	4.79	4.98
Income Over Purchased Feed Cost, \$/cow/d	6.11	7.38	5.68	5.95
Manure N, g/cow/d	500	441	469	441
Milk Urea Nitrogen, mg/dL	15.3	12.3	13.5	12
NUE, %	28	31	28	30

<sup>a</sup> Adapted from Higgs et al. [103]. <sup>b</sup> CP = crude protein; MP = metabolizable protein; DM = dry matter; NUE = nitrogen-use efficiency.

**Table 3.** Whole-Herd Milk Production, Feed Cost and Nutrient Excretion <sup>a</sup>.

Item	Base Year	Year 5	Change
Crop, ha	435	435	
Total Animals	852	1077	+26.4
Milk Cows	408	54	+33.3
Milk, kg/cow/d	30.9	33.5	+8.74
Herd Total Milk, kg/day	12,596	18,278	+45
Forage, % of Diet DM	43	59	+37
Total Feed Cost, \$/herd/d	2200	2467	+12.1
Purchased Feed Cost, \$/herd/d	1813	1375	−24.3
Manure N, kg/herd/year	140,306	116,382	−17
Manure P, kg/herd/year	19,720	14,161	−28
Manure N, kg/ha	322	268	−17
Manure P, kg/ha	43	31	−28

<sup>a</sup> Adapted from Tylutki et al. [105].

### 5.5. Diet CP and Manure Ammonia

Eleven dairy herds in Pennsylvania were used in a study to evaluate the impact of lowering diet CP on ammonia emitting potential (AEP) of manure [107]. Herds were housed in either tie-stall (six herds) or free-stall (five herds) barns. Manure systems used were gutter-scrape (four herds), flush (two herds), scrape (three herds) or gravity flow (two herds). Two trial periods were used. Phase 1 was high CP (HCP), where herds were fed their current diet. Phase 2 used diets adjusted for lower CP (LCP). Diet CP averaged 16.5% for HCP and 15.4% for LCP diets. Diet CP adjustments were done by the nutritionist working with each herd. Milk yield averaged 32.2 kg/cow/day for the HCP herds and 32.5 kg for the low CP herds. Manure N was significantly lower (2.66 vs. 2.42%) for the LCP phase. Ammonia emitting potential (AEP) was determined by incubating the manure at 25 °C with air influx of 2 L/min for 24 h. There was a 23% decrease in AEP when the LCP diets were fed. There were no changes in the methane and carbon dioxide emitting

potential between the 2 diets. The results indicate that lowering diet CP can decrease the AEP of manure.

#### 5.6. Herd Best Management Practices

The effect of implementing best management practices (BMPs) was evaluated on 15 Pennsylvania dairy farms [108]. Each herd had an option to select one or more BMPs. This decision was made in cooperation with the herd nutritionist. Seven herds adopted a BMP to lower diet CP. Diet CP was 17.2% in the base period and 15.8% after BMP implementation. Milk yield in both groups was 31.8 kg/cow/day. Fecal N decreased from 2.78% in the base period to 2.64% after BMP implementation ( $p < 0.03$ ). Urinary N decreased from 0.75% to 0.57% ( $p < 0.001$ ). Farm N imports, N volatilization, N lost by leaching and ammonia emissions were significantly lower in the LCP phase. Total net return increased significantly from USD 2230 to USD 2286 per cow when the LCP BMP was implemented.

#### 5.7. Delaware County PFM Project

Delaware County Cooperative Extension has had a PFM program in cooperation with Cornell for several years. The 2017 program reported a 23% reduction in manure P and a 7% decrease in manure N excretion in 29 herds [109]. There was an increase of USD 168/cow/year in milk income over purchased feed cost. The 2020 report for 43 herds had a 20.7% reduction in manure P excretion on herds that reduced diet P [110]. These herds also had a 7.8% decrease in manure N excretion and a USD 157/cow/year increase in milk income over purchased feed cost.

#### 5.8. Upper Susquehanna Watershed Project

Eight New York dairy herds were used in a three-year project to evaluate the impact of implementing PFM on nutrient excretion into the environment and farm profitability [111]. This was a cost-share project, in which each herd contributed 10–20% of the project cost. There were three feed companies and two nutrition consultants involved in the project. Diets were formulated by the herd nutritionist in cooperation with the PFM team. All diets were evaluated using the CNCPS program [112]. Herd visits were made 3–4 times per year by the PFM team. A PFM feed management plan was developed for each herd. Table 4 contains data on milk production, diet CP and manure N excretion. There was a 4.3% increase in milk production and a 9.7% decrease in diet CP across all herds. Manure N excretion decreased by 14%. Income over feed cost increased by USD 103/cow/year while income over purchased feed cost was USD 137/cow/year higher. The results of this trial confirm that lowering diet CP can reduce manure N excretion to the environment while improving farm profitability.

**Table 4.** Milk Production, Diet CP and Manure N in Upper Susquehanna Watershed Dairy Herds <sup>a,b</sup>.

Herd	Milk, kg/cow/d		Diet CP, %		Manure N, g/cow/d	
	Initial	Final	Initial	Final	Initial	Final
A	24.0	22.7	16.0	14.9	358	282
B	29.5	29.5	16.3	14.9	319	282
C	24.0	29.5	20.5	16.0	510	362
D	34.0	34.0	17.1	16.0	385	344
E	30.9	33.6	19.0	16.2	465	370
F	39.	39.0	17.4	16.5	456	423
G	29.5	34	16.9	16.2	422	400

<sup>a</sup> Adapted from Van Amburgh et al. [111]. <sup>b</sup> CP = Crude protein.



### 5.9. Vermont Dairy Farm Sustainability Project

This was a cooperative project initiated in 2000 [113]. Project participants were a milk cooperative, dairy processors, feed companies and the University of Vermont. Eight dairy farms were used, but one of these only had dairy heifers. The cropping program, feeding program and WFNB were evaluated on each farm. An early version of the CNCPS program was used for ration evaluation and formulation. Farm visits were made biweekly, and forages were sampled, and rations were adjusted. Milk production increased by 1.1 kg/cow/day on six of the farms. Milk production on the other farm decreased by 6.7% due to changing milking frequency from 3 to 2 times/day. Diet CP decreased from 17.7 to 17.4%, while MP supply increased by 5.1%. Rumen N balance decreased by 21%, and diet N intake was 21% lower. Diet P decreased from 0.44 to 0.37%. These results indicate that lowering diet N and P intakes improved the efficiency of nutrient use.

### 5.10. Pennsylvania Herds

Two herds in Pennsylvania were used to assess the impact of lowering diet CP. Herd A changed diet CP from 18 to 16%. Average data for a 10-month period was used to evaluate the response. Milk production (3.5% FCM) was 35.8 kg/cow/d on the 18% CP diet versus 37.8 on the 16% diet. Metabolizable protein (MP) went from 108% of the required to 99% when diet CP decreased. MUN decreased from 10.7 mg/dL to 7.8 as diet CP decreased. NUE increased from 26 to 30% when diet CP decreased. Income over feed cost was USD 0.68/cow/d higher when the 16% CP diet was fed. The comparison in herd B was made over a 3-year period. Diet CP decreased from 18.3 to 16.2% CP, while MP increased from 2978 to 3017 g/day. Milk production increased from 12,040 to 12,212 kg/cow/lactation. Feed cost was USD 0.39/cow/day lower on the 16.2% CP diet. NUE increased from 27 to 30% as diet CP was lowered. The results from these herds indicate that diet CP can be lowered while improving the efficiency of N use and improving profitability.

### 5.11. University of New Hampshire

A trial was conducted examining the impact of shifting to an LCP diet with a better amino acid balance [114]. The original diet was 18.1% CP and 3071 g of MP. Lysine was 6.37% of MP, and methionine was 1.73%. The adjusted diet was 17.2% CP and 2809 g of MP. Lysine was 6.55% of MP, and methionine was 2.2%. Both diets were fed for 11 months. Milk yield did not change, but milk true protein was 2.7 to 2.8% on the higher CP diet. Milk true protein increased from 3.12 to 3.16% on the lower CP diet. MUN decreased from 14.5 to 12.4 mg/dL when the lower CP diet was implemented. Feed cost increased USD 0.05/cow/d on the lower CP diet; however, income over feed cost increased by USD 0.65/cow/day for cows fed the lower CP diet due to the improvement in milk true protein and milk fat content.

## 6. Whole-Farm Mass Nutrient Balance

Whole-farm mass nutrient balance (WFMNB) is a tool to assist in precision nutrient imports and exports. A positive balance indicates an accumulation of nutrients on the farm. Imports include feed, fertilizer, animals, and any other nutrient-containing materials. Exports include milk, animals leaving the farm, crops sold and manure (if exported). Results of WFMNBs on 189 New York dairy farms between 2004 and 2013 were reported [115]. Whole-farm N balance (WFNB) decreased from 119 kg N ha<sup>-1</sup> to 84 kg ha<sup>-1</sup> when N fixation was accounted for. Phosphorus balance went from 10.9 kg ha<sup>-1</sup> to 6.4 kg ha<sup>-1</sup>. This is a 29% decrease for N and 41% for P. The primary driver of this change was decreased feed nutrient imports. Feed N imports accounted for 76% of this reduction, while feed P imports accounted for 74% of the change. There was no change in total farm nutrient exports. The decreases in nutrient imports were a combination of less purchased feed N and P and an increase in farm-produced feed and nutrients.

A second study examined changes in WFMNB on 54 New York dairy farms between 2005 and 2010 [116]. Reduction in mass nutrient balance per hectare was 29% for N when not considering N fixation. The change in P was  $-36\%$  per hectare. Between 63 to 78% of the farms lowered their WFMNB while increasing milk production. The primary reason for these decreases was a decrease in feed nutrient imports. The results of these studies indicate that feed nutrient imports to dairy farms have a significant impact on mass nutrient balance.

## 7. Carbon Footprint

Carbon footprint (CF) is a tool that can be used to assess the potential environmental impact of dairy production systems. This approach includes crops, animal, manure management systems and resource inputs such as fuel, electricity, fertilizer and machinery use. Carbon sequestration by crops is also estimated. Life cycle analysis (LCA) is the system used. A paper by Thoma et al. [117] reported a United States average of 1.23 kg CO<sub>2</sub> equivalent per kg of fat- and protein-corrected milk (4% and 3.3%, respectively). A second paper reported that the CF per billion kg of milk produced in the United States in 2007 was 37% of the equivalent milk production in 1944 [118]. The carbon footprint of the United States dairy industry decreased by another 19% between 2007 and 2017 [119]. The CF of milk production in the Netherlands was reduced by 35% in 2019 compared to 1990 [120]. A 22% decrease in CF in Ontario dairy herds between 1991 and 2011 was reported [121]. A paper from Denmark reported a 56% decrease in greenhouse gas (GHG) emissions per kg of milk produced between 1980 and 2010 [122]. These reports clearly indicate that the dairy industry has made significant reductions in its C while milk production has increased. A recent paper reported the CF for 19 countries [123]. The range was 0.74 to 5.99. Developed countries had CFs ranging from 0.74 to 1.53. Values from Swedish dairy farms are also available [124].

A simulation study was done using the Integrated Farm System Model (IFSM) to evaluate the impact of adopting BMP on CF in a 1500-cow dairy herd [125]. There were five feed BMPs, four manure systems and six field crop BMP's. The baseline CF was 0.99 kg CO<sub>2</sub> equivalent/kg milk. This decreased to 0.79 when the feed BMPs were implemented. This further decreased to 0.64 when the field crop and manure management BMPs were included. Similar simulations were done for a 150-cow dairy. Implementation of feed BMPs resulted in a reduction from 1.11 CO<sub>2</sub> eq./kg milk to 0.86. The addition of the field crop and manure management BMPs lowered this to 0.59. In both simulations, the feed management BMPs accounted for 48–57% of the total whole farm decrease in carbon footprint.

## 8. Lower Crude Protein Diets

The trend in the dairy industry is to formulate and feed LCP diets. A 1998 survey of the six highest producing herds in Wisconsin reported an average diet CP of 19.4%. Milk production averaged 14,142 kg per lactation in these herds. A 2019 survey of the five highest-producing herds in Wisconsin reported an average diet CP of 16.8%. The average milk production in these herds was 15,534 kg per lactation. Diet CP in New York herds decreased from 18.5 to 16.5% between 1999 to 2019 [126]. Total statewide manure N excretion decreased 8.1% during this time even though manure N excreted per cow increased by 2.7%. There was a 10.5% decrease in cow numbers, a 40.4% increase in milk per cow and a 25.8% increase in total NY milk production. A similar study in Vermont reported a 21% decrease in total manure N excretion [87]. Diet CP in the Netherlands decreased from 19.7 to 16% from 1990 to 2012 but has increased to 17% as of 2020 [127–129]. A recent paper reported decreasing diet CP from 17.5 to 15% with two different forage systems [130]. There was no change in milk production, but NUE increased as diet CP was lowered. It has been suggested that diets balanced for 15% CP can support high levels of milk production [131–135].

Table 5 contains survey information on CP in diets for commercial Holstein dairy herds selected for using low CP diets. Herd nutritionists provided the data. Diets were evaluated using the CNCPS model [108]. Diet CP was similar for the 2001 and 2019a herds, even though milk production was higher in 2019. MP and amino acid balances were higher in the 2019 herds. The 2019b herds are from a dataset of high-producing herds [136]. It is interesting that there are herds with diet CP of 15% or lower in these herds. MNE values of 38 or higher indicate that some of these herds are very efficient in using N.

**Table 5.** Crude Protein, Amino acids and Milk Nitrogen Efficiency in Holstein Herds <sup>a</sup>.

Item	2011	2019a	2019b [136]
Herds	14	26	79
Milk Yield, kg/cow/d	39.6 (32.7–52.6)	46.6 (39–57)	50.2 (44.4–58)
Milk Fat, %	3.66 (3.2–4)	3.73 (3.2–3.95)	3.71 (3.2–4.2)
Milk True Protein, %	3.08 (2.9–3.2)	3.06 (2.8–3.2)	3.06 (2.9–3.2)
CP, %	15.6 (14.3–16.3)	15.7 (13.4–16.7)	16.7 (13.9–18.2)
MP, g/cow/d	2665 (2306–3306)	3080 (2587–3592)	3191 (2885–3647)
Lysine, % of MP	6.35 (5.8–6.7)	6.66 (6.2–7)	6.62 (5.8–7.1)
Methionine, % of MP	2.04 (1.8–2.7)	2.35 (2.1–2.8)	2.36 (1.9–2.8)
MUN, mg/dL	9.4 (0–14)		
MNE, %	34 (28–38)	32.8 (28–38)	32.6 (28.9–41.7)

<sup>a</sup> CP = Crude protein; MP = metabolizable protein; MUN = milk urea nitrogen; MNE = milk nitrogen efficiency.

Other papers suggest that diets less than 15% CP may be adequate if the amino acids supplied meet the amino acid requirement [123,126]. A survey of nutritionists reported that 72% of the respondents were formulating diets with lower CP than they were 3–5 years ago [137]. A review paper concluded that diets with 14–15% CP are adequate in supporting health and reproduction [134].

## 9. Diet Formulation

Crude protein has been the most common approach used in balancing dairy diets. Adjustments made include rumen-degradable (RDP) and rumen-undegradable protein (RUP). The 2001 Dairy NRC publication evaluated the relationship between CP and milk production [138]. An equation using both CP and DMI was used to assess the relationship between CP and milk production. The dataset included 393 treatment means from 82 protein trials. The regression equation for milk production had a  $r^2$  of 0.29. This result highlights the fact that dairy cows do not have a CP requirement. They do have requirements for absorbable amino acids at the intestinal level. It was suggested that MP be used to formulate diets rather than CP. Metabolizable protein is composed of microbial protein synthesized in the rumen and RUP. The 2001 NRC did not establish amino acid requirements but did use a break point analysis to estimate lysine and methionine levels in dairy diets to maximize milk protein yield (MPY). The estimated values were 7.2% of MP for lysine and 2.4% for methionine. Further examination of dose response curves resulted in a practical recommendation of 6.6% lysine and 2.3% methionine [114]. Schwab and Ordway (114) evaluated >300 diets from published research trials using the NRC 2001 model. The  $r^2$  was 0.65 between actual and predicted MP milk. A second comparison using data from commercial herds reported an  $r^2$  of 0.72 between actual and predicted MP milk [113]. These results indicate the value of using MP rather than CP to formulate dairy cattle diets.

The 2021 NASEM nutrient requirement publication suggests moving to formulating diets for individual EAA's rather than MP [139]. An equation to predict milk protein yield (MPY) using five essential amino acids (EAA) was developed. A review paper outlines the rationale for this approach [140]. The increased use of amino acid balancing is one area that can be expanded [141]. A trial used three diets that were isocaloric and had a positive rumen N balance [142,143]. A neutral diet was targeted to meet EAA requirements. The negative and positive diets were formulated to be one standard deviation below or above the neutral diet

in EAA. Milk yield, ECM, milk true protein yield and milk fat yield were significantly higher for the neutral and positive diets than the negative diet. Differences between the neutral and positive diets were not significant. A second trial was done using four diets [144]. The base diet was 13.5% CP, which was adequate for ME but limited in rumen N, methionine, and MP. The positive diet was adequate in ME, MP, rumen N, and balanced for EAA. Two intermediate diets were also formulated. One was adequate in ME and methionine but limited in rumen N and MP. The other diet was adequate in ME, methionine, and rumen N but limited in MP. ECM, milk yield, milk true protein yield and milk fat yield were significantly higher for the positive diet compared to the base diet. In these trials the CNCPS v7 model [145] was used to examine the use of EAA in balancing diets.

A comparison of using MP or three EAA to formulate diets for Canadian dairy farms has been reported [146]. The amino acids used were lysine, methionine and histidine. Using the amino acid approach, a 3.8% decrease in farm N balance and a 4.3% increase in efficiency of N use was reported. Net farm income was 4.5% higher.

## 10. Diet Formulation Models

The use of diet formulation models provides an opportunity to balance dairy cattle diets to optimize rumen function, decrease excretion to the environment and feed efficiency. A commercial program was used to assess the economic impact of formulating diets weekly or monthly [147]. This program uses CNCPS biology. Return over variable costs were USD 25,000 per year higher when diets were formulated weekly. This is USD 83 per cow per year.

A review of some of the models is available [148]. A recent paper outlined the role and limitations of mechanistic models [149]. There are several formulation models available. These include both linear and non-linear models. Other types of models are response and mechanistic [150–157]. A survey of nutritionists found that about 60% of the respondents used the CNCPS model or one of the commercial programs licensed to use the CNCPS biology [137]. The CNCPS model [112] can provide information on N and P excretion and CH<sub>4</sub> and CO<sub>2</sub> emissions. Table 6 contains the environmental outputs for a diet balanced for 43 kg of milk with a DMI of 23.8 kg. This diet is 16.6% CP, 31.4% NDF, 5% fat and 26.6% starch and provides 2769 g of MP/cow/d. The diet is 62% forage with 2.7 ratio of corn silage to alfalfa silage. This diet met 103% of the ME and 101% of the MP requirements.

**Table 6.** CNCPS Environmental Outputs for a Diet Balanced for 45 kg of Milk and a Dry Matter Intake of 25 kg <sup>a,b</sup>.

Fecal Excretion kg/cow/d	43.5
Urine Excretion, kg/cow/d	20.9
Fecal N, g/cow/d	242
Urine N, g/cow/d	183
Total Manure N, g/cow/d	420
Productive N/Total N, %	35
Productive N/Urinary N	1.26:1
Manure N/Total N, %	65
Fecal P, g/cow/d	53
Urine P, g/cow/d	1
Total Manure P, g/cow/d	54
Productive P/Total P, %	41
Manure P/Total P, %	59
CH <sub>4</sub> , g/kg Milk Yield	10.1
CO <sub>2</sub> , g/kg Milk Yield	323
NH <sub>3</sub> Potential <sup>c</sup> , g	116

<sup>a</sup> Diet is 16.1% CP, 31.7% NDF, 4.2% fat, 25.3% starch and provides 2863 g of MP/cow/d. <sup>b</sup> Cornell Net Carbohydrate and Protein System [112]. <sup>c</sup> Ammonia emission potential set at 65% of urine N (g/cow/d).

## 11. Grouping of Dairy Cattle

Grouping strategies on dairy farms provides an opportunity to improve the efficiency of nutrient use, decrease the number of overfed cows, decreases nutrient excretion and lowers feed cost, and can improve income over feed cost. The goal is to decrease the variability of milk production within the group. Several papers have described methods and considerations for grouping [158–163]. The challenge is determining the level of milk production to balance the diet for. Balancing for one standard deviation above the group mean should meet the nutrient requirements for 83% of the cows in the group [162]. A diet would be balanced for 50 kg of milk for a group averaging 40 kg milk with a standard deviation of 10 kg of milk. If the standard deviation was 5 kg, then the same group would be balanced for 45 kg of milk.

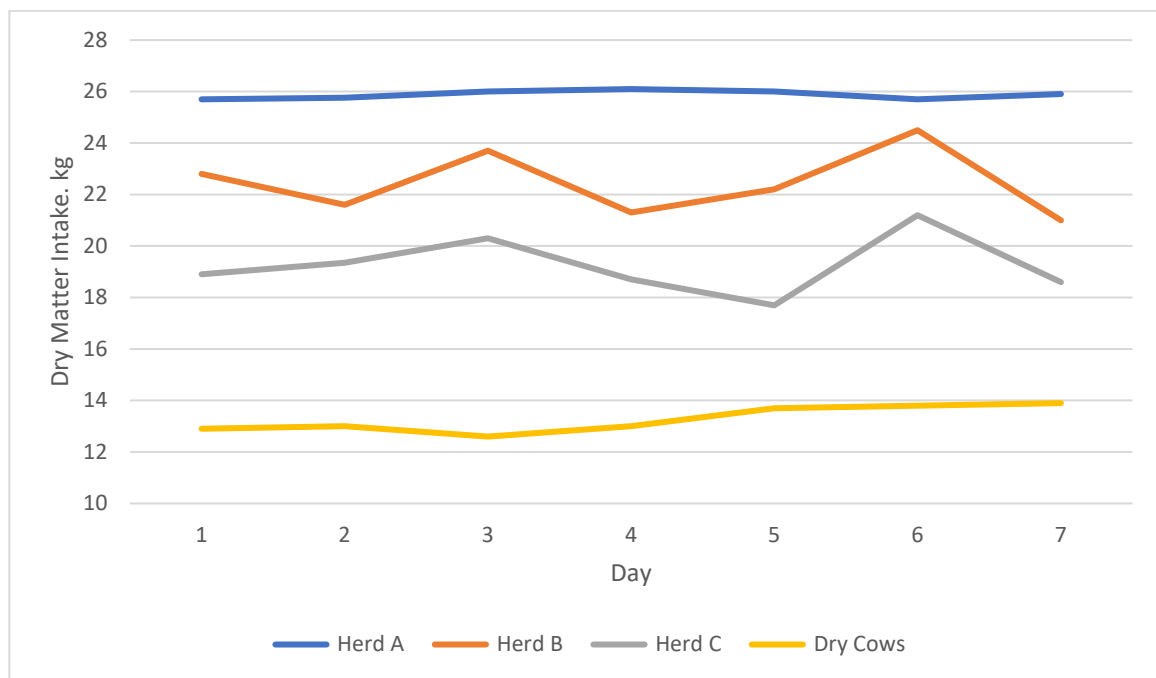
The impact of cluster or OptiGroup methods of grouping was evaluated on seven Wisconsin dairy farms [160]. The average income over feed cost in a two-group system was USD 8/cow higher using the OptiGroup approach. This increased to USD 12/cow in a three-group system. The impact of nutritional grouping in a herd with 2374 cows and 14 pens was evaluated [161]. Pens were regrouped weekly, and diets were adjusted. There was a USD 31/cow/year lower feed cost using the nutritional grouping strategy. There was also a decrease of 15 g/cow/d in diet N intake. The effect of grouping was examined in a 600-cow New York herd averaging 41 kg of milk. The herd had a fresh-cow and high-cow groups. A late lactation diet was formulated and fed to the herd. There was no change in herd milk production, but feed cost was reduced by USD 0.65 cents per cow per day (USD 237/cow/year). Herd N excretion decreased by 6.2% and P by 2% by adding the third group.

## 12. Feed Management Systems

A key factor for success in PFM is improving the consistency and reducing the variability of the daily feed management program [164–167]. Several electronic feed management programs are available for use on dairy farms [168]. Sixteen percent of the farms reported using a feed management system [168]. Ten percent of herds with less than 100 cows used a feed management system. In larger herds (>500 cows), 52% of the herds were using a feed management system. These programs have weigh cells on the mixer wagon and can record the quantity of each ingredient added to the mix. Information on the total quantity of feed delivered to each animal group can be recorded. If feed refusals are collected and weighed, then group DMI can be determined. Table 7 is an actual example of a TMR mixed on a dairy farm. This is an excellent mix with a small variation between the target feed amount and the amount added. Figure 1 contains DMI over a 7-day period for 3 herds and 1 dry cow group. Herd A and the dry cows had a small variation in DMI over the 7-day period. Diets could be formulated with a small safety margin above the requirements in these groups. The larger daily variation in DMI in herds B and C make it difficult to formulate diets with small safety margins and would be expected to have larger variation in herd daily milk production.

**Table 7.** Total Mixed Diet Mix Sheet.

Feed	Target Amount, kg.	Amount Added, kg.	Deviation, %
Corn Silage	3130	3144	0.45
Alfalfa Silage	1283	1297	1.1
Corn Grain	402	398	−1.0
Distiller's Grain	187	189	1.06
Protein Mix	470	471	0.2
Total	5472	5499	0.5%



**Figure 1.** Daily Dry Matter Intake in Commercial Dairy Herds, kg.

### 13. Role of NIR

Near infrared spectroscopy (NIRS) technology is routinely used in commercial forage-testing laboratories to measure organic constituents in feed and forage samples. This technology is now available in portable devices that can be used on farms for rapid analyses. The initial use was to determine forage dry-matter content [169,170]. The ability to determine nutrients, such as protein and fiber, is now becoming available. A review paper on the potential use of NIRS on dairy farms is available [171].

A second application of NIRS is as part of an integrated feed management system. In this system, a NIRS unit is installed in the front-end bucket used to load silage from bunker silos. This gives a real-time forage DM value that is used to adjust the quantity of wet silage added to the mixer wagon to maintain a constant amount of silage DM in the mix. A trial was conducted on a commercial dairy herd comparing weekly ingredient DM adjustments (control) compared with a treatment group with ingredient DM adjusted for each load of feed mixed [172]. Samples of the TMR and feed refusals were taken weekly for feed analysis. Cows were milked three times per day, while the TMR was fed twice a day. Pens were balanced by milk production and days in milk. Analyzed TMR's were similar for DM, CP, NDF, starch and ash. Fat content was significantly higher in the control TMR (4.7 vs. 4.4%). There were no significant differences in DMI, milk production, 3.5% FCM, milk fat and protein yield and feed efficiency. Milk production averaged 52.8 kg/day for cows on this trial. The authors indicated that this herd had an excellent feed management program and that the results of using the NIRS system could be different in a herd with a feeding program with more variability. The NIRS based system did a respectable job of detecting changes in forage DM and adjusting the quantity of forage added to maintain the amount of forage DM in the diet.

A second study used seven Italian dairy herds [173]. All herds had a feeding system with the NIRS unit on the TMR wagon. All herds were fed a TMR once per day. This was a crossover trial consisting of two consecutive periods of 14 weeks each. The DM content of silages was determined daily in both periods. The feeding system was switched on/off and off/on between the two periods in each herd. In one period, no adjustment on the quantity of silage added to the mixer wagon was made. In the other period, the quantity of silage added to the mixer wagon was adjusted using the daily DM value. There were no significant differences in diet NDF and starch between the periods. No differences in milk

yield or the percentage of milk fat and protein were detected. The variability in the TMR for nutrient content and DM was lower when the NIRS-based feeding system was used. If only the data from the last week of the period when the NIRS-based feeding system was there is considered, then there was an increase of 2.4% in milk production and a 1.3% decrease in the diet DM fed. There was also about a 5% decrease in feed cost per kg of milk.

#### 14. Conclusions

The dairy industry has already made significant strides in improving milk production while lowering its impact on the environment. Milk yield in the United States increased from 2074 kg/year in 1944 to 9193 in 2007 [118]. The carbon footprint to produce 1 billion kg of milk decreased by 37% during this same time. An updated analysis reported that milk yield had increased to 10,406 kg/year in the United States as of 2017 [119]. Greenhouse gas emissions per 1 million metric tons (MMT) of energy-corrected milk in 2017 were 80.8% of 2007. During this time, the amount of land required to produce 1 MMT of milk in 2017 was 79.2% of the land needed and 69.5% of the water. The amount of feed needed in 2017 was 82.7% of that needed in 2007.

A report characterized changes in the California dairy industry between 1964 and 2014 [174]. Milk production per cow increased from 4850 to 10,600 kg/cow/year. Production of 1 kg of ECM resulted in emission of 2.11 kg of CO<sub>2</sub> equivalents in 1964 compared with 1.12–1.16 in 2014. This is a 45 to 47% decrease. Methane emissions were 54–56% lower in 2014. Water use was 88–90% lower in 2014 versus 1964. Land required for crop production decreased by 89–89% during the 50-year period. A key factor in reducing the land required for crop growth was the increase in crop yields per hectare.

The results of the on-farm trials reported in this paper have consistently found that decreases in nutrient excretion into the environment can be made while maintaining or improving milk production. Feed cost is usually lower, and income over purchased feed cost is higher when diets are adjusted to lower nutrient excretion and improve efficiency of nutrient use. It is important to point out that most of the diet adjustments made in these trials did not consider amino acid balance. Balancing for amino acids should provide the ability to further lower diet CP. In the on-farm trials reported, diet CP was reduced to 5 to 22% with no negative impact on milk production. MUN was 2–3 units lower in trials where it was measured as diet CP decreased. The efficiency of nitrogen use increased by 2 to 3 units as diet CP decreased. Diet P was lowered to meet requirements with no adverse effects on milk production or reproduction. A key factor in conducting these on-farm trials was the active participation of the herd nutritionist. Being involved gave them more confidence to adjust diets by lowering CP and P. One result was that these nutritionists implemented these diet adjustments in other herds that they worked with.

There are additional opportunities for further diet and management changes to further reduce nutrient excretion and increase the efficiency of nutrient use. There may also be a role for artificial intelligence in identifying potential technologies that could be implemented [175,176]. Increased use of robotic feeding systems is one example that may be advantageous in terms of labor efficiency and precision feeding. A key principle is to reduce variation in the forage and feeding program.

Improvement of models for diet formulation and the herd size (herds larger than 500 cows were 2 to 5 times more likely to adopt precision technologies) will assist in improving efficiency of nutrient use and decreasing nutrients provided above requirements [149,177–183]. The increased use of amino acid balancing is one area that can be expanded [141,180]. Schwab [141] provided some guidelines for balancing diets for amino acids. The starting point is to provide a blend of rumen-fermentable carbohydrates and physically effective fiber in combination with adequate RDP to maximize microbial protein production. The next step is to use high-lysine protein supplements to meet the lysine requirement. These are often high in rumen-undegradable protein due to heat treatment. The next step is using a rumen-protected methionine source. In the future, there may be machine learning or artificial neural network approaches to diet formulation [149,176].

Sustainability is an important topic regarding the future of the dairy industry [181,184–189]. Economic, environmental, and societal concerns are the three common terms used to describe sustainability; however, it has been suggested that animal well-being and health should be added [187]. Precision feed management has a significant role in determining sustainability of a dairy farm. A survey of 171 Italian dairy farms feeding total mixed rations was done to examine relationships between sustainability and milk production [181]. Diet global warming potential (GWP) was calculated for each farm as kg of CO<sub>2</sub> equivalents. The average GWP was 13.7 with a standard deviation of 3.71. A GWP of  $\geq 27$  was determined in 8.7% of the herds while 28% of the farms had a GWP < 11. A simulation study was done to assess the impact of altering dairy diets on greenhouse gas emissions [190,191]. Carbon footprint was reduced by 20 to 26% when feed, cropping and manure management BMPs were used.

The dairy industry faces several challenges in the future that will impact the ability to further reduce nutrient excretion and emissions to the environment. One of these is the potential impact of climate change on crops and animals [178,179]. Crop yields are projected to decrease in many crops grown for animal feed. Heat stress can have both short- and long-term impacts on animal health and productivity. Drought, water availability, public perception of animal agriculture, labor shortage, the role of robotic milking and feeding systems and economics all will impact the future of the dairy industry. A major factor is national and state regulations. There are several countries that are imposing regulations for N, P, ammonia, and methane. Some of these will potentially have a significant negative impact on the dairy industry. In most cases, these changes in regulations are made without input from the dairy industry. The dairy industry needs to be proactive and bring science-based information into the regulatory discussion. In the United States, the National Milk Producers Federation and the Innovation Center for United States Dairy are both highly active in programs using science-based information to the nutrient management and sustainability discussion.

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