

Cow of the Future Research Priorities for Mitigating Enteric Methane Emissions from Dairy

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July 2011
Working draft

This document reflects the current work of the Cow of the Future team. It should be considered a *working draft* intended to stimulate conversation within the academic and business community to advance our collaborative efforts to reach the dairy industry's voluntary goal to reduce greenhouse gas emissions for fluid milk by 25% by 2020.

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Support for the project has been generously provided by the David and Lucile Packard Foundation.

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Executive Summary

The Innovation Center for U.S. Dairy has set a goal of reducing enteric methane missions (per lb. fluid milk) from dairy cattle by 25% by 2020 by implementing the *Cow of the Future* project. It was clearly stated by EPA (2005) that “improving livestock productivity so that less methane is emitted per unit of product is the most promising and cost effective technique for reducing emissions in the U.S.”. It is also clear that historical improvements in dairy production have reduced methane emissions per unit of milk substantially (Capper et al., 2009). Implementation of existing technologies and management practices in the U.S. dairy industry along with continued genetic progress in milk yields is expected to result in 10 to 12% reductions of methane emissions per unit of milk over the next decade. To achieve the additional 13 to 15% reduction to reach the overall goal of 25% requires investment in research to identify and develop new strategies and technologies. Conservative estimates suggest that additional reductions of 15 to 30% can be achieved, dependent upon the development of new strategies and technologies and their adoption by the U.S. dairy industry (Figure 1).

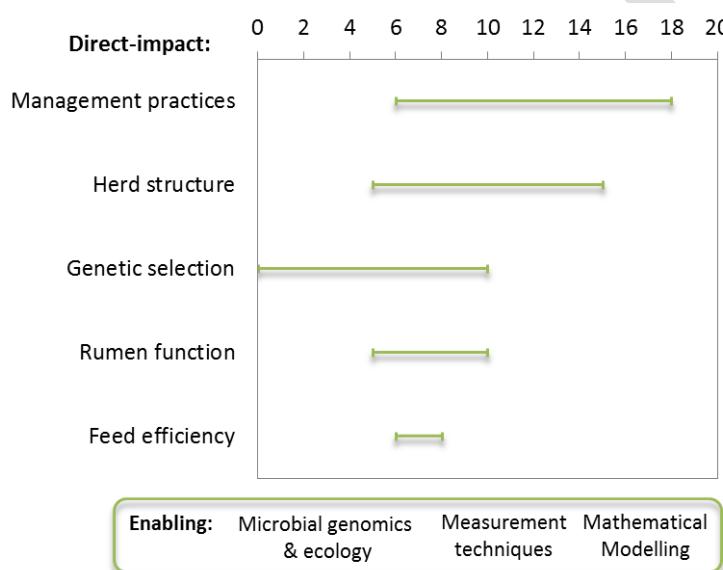


Figure 1. Potential reductions in methane per unit of milk (%). Development of new strategies and technologies through research in these areas can significantly reduce methane per unit of fluid milk in U.S.

This *Research Priorities* document has identified eight major research areas for the development of new strategies and technologies. Focus on these areas will reduce redundancy, improve research efficiency, and increase the overall impact of the research to the dairy industry and to the general public. Several of these areas are not ones that have been widely discussed or recognized to reduce methane emissions from dairy cattle, but they have significant potential to contribute to the goal of reducing methane per unit of milk. This research will also contribute to improvements in dairy profitability, as well as enhancing environmental stewardship and consumer acceptance of dairy products.

Criteria for Future Methane Mitigation Approaches and Technologies

To systematically evaluate proposed research projects regarding their potential for methane reduction and the corresponding impacts on dairy profitability, environmental sustainability,

consumer acceptance of dairy production practices and products, and animal health and welfare, the Advisory Group recommends applying the following criteria:

1. Scientific soundness of the approach
2. Potential for productive outcomes of the research project
3. Magnitude of the approach's potential to reduce enteric methane emissions
4. Economic feasibility of the application/approach, both in terms of the costs of implementing the mitigation approach and avoiding a negative impact on farm profitability.
5. Adoptability or lack of hurdles in applying the mitigation approach on U.S. dairy farms
6. Years to application
7. Other environmental impacts of the approach (water use, land use, nitrogen and phosphorus pollution)
8. Consumer acceptance of the approach
9. Impact on animal health and welfare
10. Originality of the research

Potential Impacts: Benefits and Risks

In addition to reductions in methane emissions, the research in all of the areas has the potential to lead to improvements in dairy profitability, environmental sustainability, consumer acceptance of dairy production practices and products, and animal health and welfare. Because research areas have been identified in this *Research Priorities* document rather than specific mitigation strategies and technologies that will be the outcomes of such research, only general comments regarding profitability, consumer acceptance, environmental considerations, and animal welfare can be made here. However, these considerations are vitally important in determining which methane mitigation research and development projects should be pursued. Adoption of mitigation strategies by dairy producers will depend on these considerations as well as the feasibility of implementation and regulatory policy. Adoptability and time-to-market should also be addressed in the research and development process.

Of the eight research areas, three areas provide the foundation and integration of knowledge and research tools that will strengthen research efforts in the other five areas. They are: Area 1- *Rumen Microbial Genomics and Ecology*, Area 7- *Development and Refinement of Methane Measurement Techniques*, and Area 8- *Modelling Efforts to Quantitatively Integrate Knowledge*. Consequently, the impact of these areas on methane mitigation and dairy sustainability is indirect and will be manifested by their contribution to the strategies and technologies developed in the other five research areas.

The five *Research Priorities* areas (Areas 2 through 6) that have direct impacts on methane emissions have moderate (5 to 15%) to high (>15%) reduction potential (figure, p.1). These areas include: Area 2- *Rumen Function and Modifiers*, Area 3 – *Enhancing Feed Quality and Feed Ingredient Usage to Improve Feed Efficiency*, Area 4 - *Genetic Approaches to Increase Individual Cow Productivity*, Area 5- *Management Practices to Increase Individual Cow Productivity*, and Area 6 – *Management of Herd Structure to Reduce Number of Cow-Days of Non-Productive Animals*. Mitigation strategies and approaches arising from these areas also have moderate potential to improve dairy profitability through increases in production efficiency at the individual cow or herd level. This would be a win-win for the dairy industry, reducing methane emissions while improving net profits. Of course, the cost of implementing the mitigation approaches will be a factor in profitability.

Additional environmental benefits in reducing methane emissions can occur through some strategies and technologies. If total feed consumption is reduced because of increased production efficiency and fewer animals are required to maintain milk supplies (Areas 3 to 6), less water will be required for growing feed and animal consumption. Water needed to operate dairy facilities may or may not be affected. Alternatives for cooling cows that require less water than current methods will reduce water usage, and opportunities may exist to decrease water use in manure handling systems. Mathematical models that can predict water use on a whole farm or in a geographical region will be needed to quantitatively evaluate the impact of methane mitigation strategies on water use (Area 8). Nitrogen and phosphorus pollution from crop operations and manure handling may also be affected; these topics are being addressed in the *Dairy Farm Smart*, *Dairy Power*, and *Biogas Capture and Transport* projects sponsored by the Innovation Center for U.S. Dairy. The dairy industry should also receive partial credit for the environmental benefit attributed to biofuels, as the ethanol and biodiesel industries would not be economically viable if the co-products were not consumed by ruminant livestock.

Most methane mitigation strategies and technologies that are currently being proposed and might be developed are expected to have little or no impact on dairy product quality or nutritional value and thus would be acceptable to consumers. The application of some technologies may be more acceptable to consumers than others, i.e. feeding naturally occurring compounds vs. synthetic compounds to modify rumen microbial function (Area 2). Production practices that improve dairy cow health and welfare (Areas 5 and 6) and reduce the environmental impact of dairying (all Areas) will be very acceptable to consumers.

The *Research Priorities* described in this document have the potential to meet or exceed the Innovation Center's goal of a 25% reduction in methane emissions, and many of the research areas will complement each other. There are very good scientists at institutions across the U.S. with the capabilities of conducting the needed research. The *Cow of the Future* project needs to address issues in funding availability, increase opportunities for training future scientists, and promote facilitation of scientific exchange and collaboration. As an additional consideration, outcomes in many of the research areas would benefit the beef industry as well. There is substantial synergy that can be captured with the dairy and beef industries working together.

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Overview

In January 2009, the Innovation Center for U.S. Dairy announced a voluntary goal to reduce greenhouse gas (GHG) emissions of a gallon of fluid milk — from farm to retail — by 25 percent by 2020. The goal is supported by the [U.S. Dairy Sustainability Initiative – A Roadmap to Reduce Greenhouse Gases and Increase Business Value](#), which defines the action plan for how the industry can reach its ambitious goals. The Roadmap prioritizes 10 projects across the fluid milk value chain — from production of feed for dairy cows to the processing, packaging and distribution of milk. Each project has undergone a review process to ensure its assumptions are sound, its potential fully assessed, and the best resources of the industry are being leveraged. The projects range from those ready to implement to those requiring systemic change and adoption of new technologies. This project, *Cow of the Future*, addresses enteric methane produced by cows during the process of feed digestion. Two other projects, *Dairy Power* and *Biogas Capture and Transport*, focus on methane capture from manure, *Dairy Farm Smart* provides tools to optimize the retention of nutrients such as nitrogen on farm for crop production, and *Farm Energy Efficiency* encourages the adoption of energy audits on dairy farms. The remainder of the projects focuses on processing, manufacturing, and transportation.

Enteric methane is the largest contributor to greenhouse gas emissions in the dairy value chain (Figure 1), with emissions from manure the second largest contributor, and fossil fuel use across the chain the third largest contributor. Total enteric methane emitted from all livestock in the U.S. is estimated to be 139 Tg CO₂ equivalents/year (EPA, 2009). Of this, approximately 35 Tg CO₂ equivalents per year are attributable to dairy cattle (Figure 2, LCA study, 2010). Enteric methane emissions from dairy cattle comprise approximately 25% of the total greenhouse gas emissions associated with dairy production in the U.S. The Innovation Center's goal is a reduction of 25% in methane produced per gallon of fluid milk consumed.

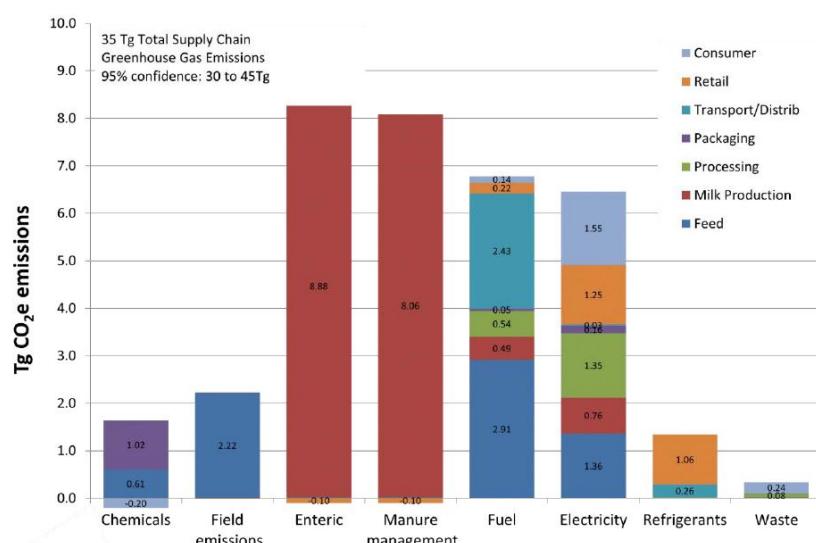


Figure 2. Cumulative greenhouse gas emissions in the dairy production chain for 2007. Units are Tg or million metric tons (LCA study, 2010).

The *Cow of the Future* project currently has two primary objectives. The first identifies and prioritizes existing technologies and practices that can reduce enteric methane emissions, and the second evaluates research opportunities that will lead to the development of future mitigation technologies and practices. This *Research Priorities* document summarizes the evaluation of research opportunities conducted by the Advisory Group and their recommendations. Reductions in methane emissions throughout the remainder of the *Research Priorities* are expressed as lb. methane per lb. of fluid milk or energy-corrected milk produced, which accounts for methane emissions associated with all dairy products, not just fluid milk consumption.

Formation of the Advisory Group

The Innovation Center's goal is to execute a national research prioritization in collaboration with leading research institutions. The *Cow of the Future* project will help prioritize research initiatives, assist in securing funding for U.S. research efforts and international collaboration, and coordinate with international research organizations to share findings and eliminate duplication of effort. Through existing contacts, Innovation Center personnel identified key leaders in rumen microbiology, dairy cattle nutrition, animal genetics, and dairy herd management from across the U.S. who are associated with land-grant universities and livestock industries (for a complete list of this Advisory Group see Appendix B). These experts form the core of the Advisory Group and have willingly contributed their time and expertise to provide advice on research to reduce enteric methane emissions from dairy cattle production and to make recommendations for future research directions and needs. Those recommendations are the heart of this *Research Priorities* document.

Formulation of the Research Priorities

Over the course of five months beginning in November 2010, the Advisory Group aided in soliciting Expressions of Interests (EOI) from other U.S. researchers, identified eight areas for future research in methane mitigation, and contributed to the formation of these Research Priorities white paper. The Innovation Center for U.S. Dairy asked researchers from land-grant agricultural colleges, veterinary colleges, and USDA Agricultural Research Stations across the U.S. to provide an outline of their future research that is likely to impact methane production. More than 50 investigators from over 20 institutions responded with Expressions of Interest (Appendix A). The EOI complemented the overall view of the Advisory Group with regards to future research in enteric methane mitigation strategies, and demonstrate that there are substantial institutional resources available for future research in this area. In addition to the input of both the Advisory Group and researchers who submitted EOI, this Research Priorities document has also undergone a thorough scientific review by additional experts who are external to the Innovation Center for U.S. Dairy and the Advisory Group.

Timeline for Development & Application of Research

The Advisory Group recognizes that the timeline of taking research outcomes and developing them for on-farm application is variable and difficult to predict in the early stages of research. The panel recommends that research projects with a range of development timelines be considered for funding for the U.S. Dairy industry to reach its goal of reducing GHG emissions. This is generally referred to as a research and development "pipeline" with many projects entering the initial phases and a few coming out to be implemented as successes. The Advisory Group thinks that the growing complexity of the dairy industry and the need to evaluate

systems increasingly requires larger teams of scientists with various areas of expertise and that truly novel solutions often arise from the curiosity and diversity of individual researchers. A primary objective for the Cow of the Future project is to foster team development by coordinating communication among scientists and their use of facilities and equipment. This Research Priorities white paper identifies eight research areas where teamwork and collaboration should be fostered to reduce redundancy, improve research efficiency, and increase the overall impact of the research to the dairy industry.

The U.S. Dairy Industry

In 2010, U.S. dairy farmers produced over 193 billion lbs. of milk, worth approximately \$36.9 billion (USDA/ERS, 2010). Over the past decade, total milk production has increased in concert with the increased demand for dairy products from the growing population and increasing exports. This increase in production was achieved without increasing cow numbers, which have held steady for nearly two decades at 9.0 to 9.3 million cows (USDA/ERS, 2010). Production efficiency has therefore increased substantially with average production currently at 21,000 lbs. per cow per year. Farm consolidation has continued, with 33% of dairy farms exiting the industry during the past 10 years. Currently, there are approximately 65,000 dairy farms in the U.S., mostly owned by families (USDA/ERS, 2010). Herd sizes range from less than 25 cows per farm on small, pasture-based, operations to more than 4000 cows on the largest operations. A large portion of the milk is produced on the larger farms that are able to capture economies of scale (USDA/ERS, 2007).

The U.S. dairy industry has become “westernized” with development of strong dairy regions in Idaho and the Texas Panhandle/eastern New Mexico area along with continued growth in the Central Valley of California during the past decade (Figure 3). The top ten dairy producing states are: California, Wisconsin, New York, Idaho, Pennsylvania, Minnesota, Texas, Michigan,

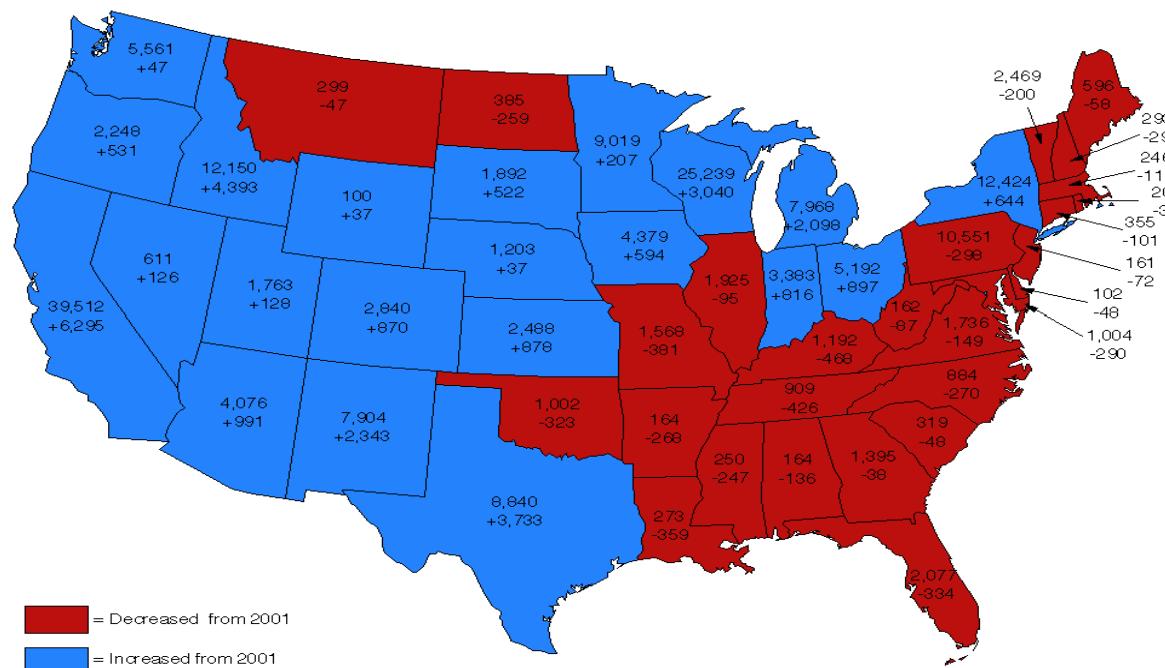
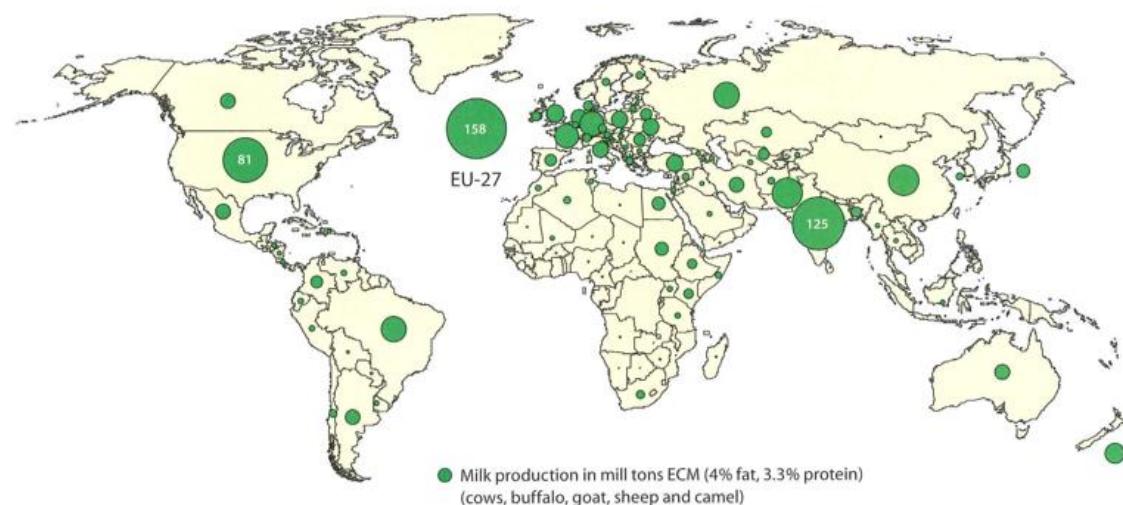


Figure 3. U.S. Milk production in 2009 and change (+/-) from 2001 (million lbs; USDA/ERS, 2010).

New Mexico, and Washington (USDA/ERS, 2010). The U.S. is one of the largest dairy producers in the world (Figure 4) and has become a net exporter of dairy products. The major products exported by the U.S. are skim milk powder, whey protein concentrates, and butter (USDA/ERS, 2010). During the past decade, dairy exports from the U.S. have increased and accounted for 12% of total milk production in 2010 (USDA/ERS, 2010). U.S. exports fluctuate from year to year, dependent upon world market conditions. This fluctuation has significantly impacted the price U.S. dairy producers received during the past five years.

Milk production world-wide



*Data: Milk production 2008 in ECM.
Source of data: National statistics, FAOSTAT, for some countries estimates.*

Figure 4. Global milk production in million metric tons (IFCN, 2009). The five largest exporters of dairy products are New Zealand, Australia, the EU, U.S.A., and Argentina. Consumption is not displayed.

Areas of Research

Eight areas of research were identified with potential to reduce enteric methane emissions. Six areas focus on different levels of biological organization including the rumen microbes, the whole animal, and the herd structure. A seventh area deals with methane measurement techniques, and an eighth area integrates the knowledge in a quantitative framework or mathematical model (Figure 5). Each area of research is described separately on the following pages. A brief summary of the “state of the art” within the area is provided, future research needs identified, and the potential for reducing enteric methane emissions placed into perspective of the whole enterprise.

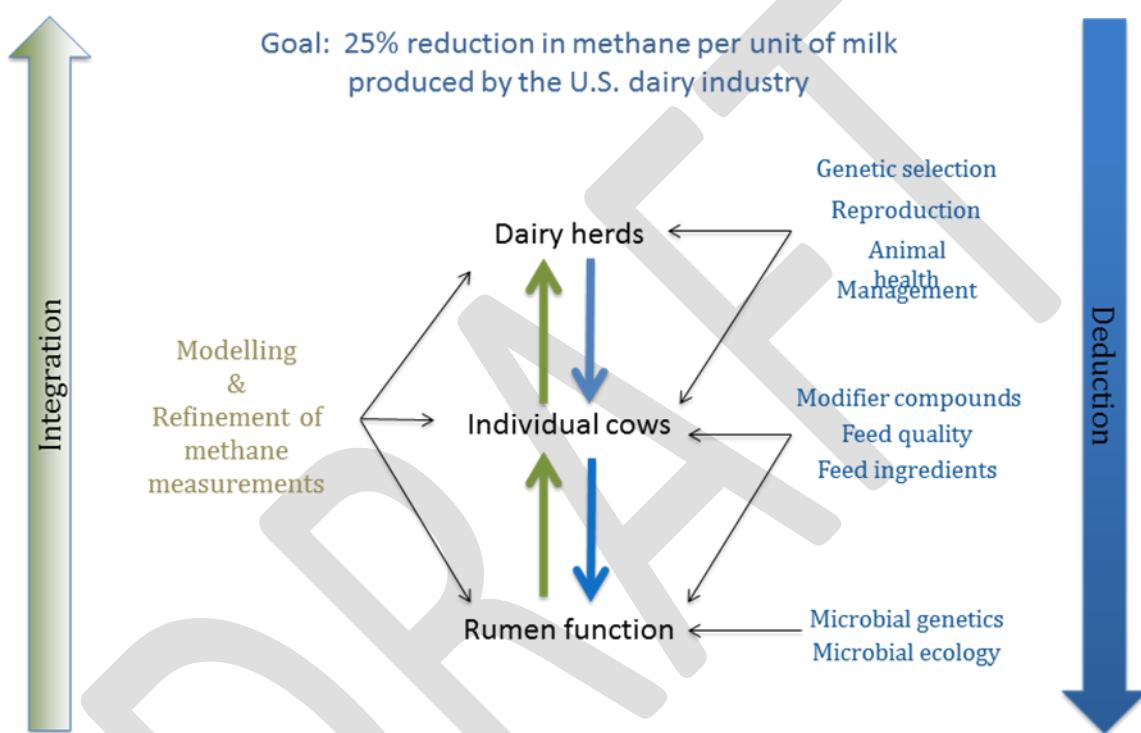


Figure 5. How methane mitigation research areas fit together to reduce methane emissions.

Area 1. Rumen microbial genomics and ecology

Summary: Research on rumen microbial genomics and ecology builds a solid foundation for development of technologies and practices for mitigating enteric methane emissions. As such, it holds tremendous potential to reduce the impact of dairy and beef production on GHG emissions. Improved knowledge of rumen ecology and function will also lead to improvements in nutrient utilization and milk component synthesis, thus benefitting dairy profitability.

Methane is one of the end-products of the anaerobic fermentation which occurs in the rumen, reticulum, and the large intestine of cattle (Figure 5). With the absence of oxygen, methane is a predominant hydrogen sink (Figure 4). Through inter-species hydrogen transfer, the methanogens convert hydrogen gas to methane efficiently capturing the hydrogen gas produced by fermentative bacteria, protozoa, and fungi. The reactions producing hydrogen would be

thermodynamically unfavorable otherwise, so methanogenesis allows a higher energy yield by many non-methanogenic microbes (Wolin et al., 1997). Although methane production benefits many microbes in the rumen, especially those that degrade fiber, methane also represents an energetic loss to the animal, whereas other end-products of the microbial breakdown of feed provide both energy and protein to the cow.

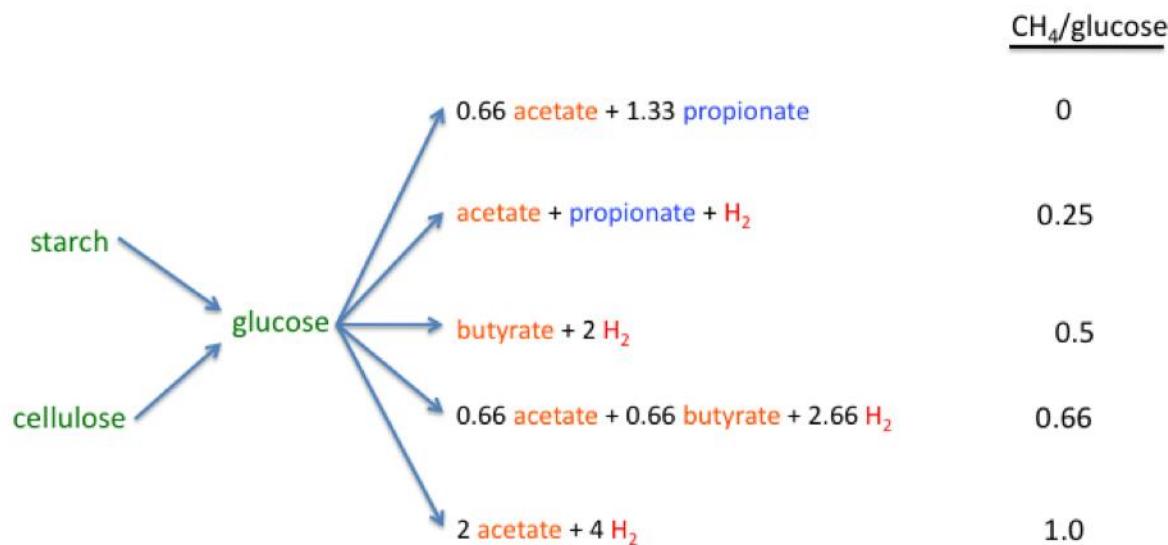


Figure 5. Fermentation of six carbon sugars by rumen microbes to volatile fatty acids (acetate, propionate, and butyrate) and hydrogen and its contribution to methane (CH₄) production. Multiple pathways exist and due to the metabolic flexibility engendered, the proportion of methane (moles) produced per mole of glucose is variable. For simplicity CO₂, H⁺, and the fermentation of five carbon sugars are not shown. Adapted from Janssen, 2010.

Research on microbial genomics and ecology has the potential to enhance our current understanding of the interrelationships between species and lead to the identification and evaluation of better opportunities for modifying rumen function to reduce methane generation while still optimizing digestibility and microbial function. Specific knowledge and understanding that is needed to further this area include: a better understanding of the inter-relationships of protozoa, methanogens, and bacteria; increased understanding of host (cow)-microbe interactions, quantitative knowledge of rumen function, and improved understanding of how the microbial population as a whole (i.e. microbiome) reacts to dietary manipulation and feeding practices including, but not limited to, rumen modifiers (Area 2). For example, we know that cows fed the same diet can have widely different microbiomes that are associated with varying degrees of milk fat concentration (Weimer et al., 2010b). Host specificity for ruminal microbial community composition, ruminal pH, and VFA concentrations appears to be substantial, as shown by their quick reestablishment after near-total exchange of rumen contents between cows (Weimer et al., 2010a). In addition, bouts of acidosis could flare up intermittent bursts of undesirable bacteria (Khafipour et al., 2009, 2011) that have been linked to a host's response to depress milk fat production (Zebeli and Amatayakul, 2009). Yet, while examining key concepts like this, the statistical associations are completed after the fact and often do not reveal which ruminal microbial species are responsible for shifts in bioactive end-products such as methane, or induce a change in milk or milk components versus those that are simply occupying a niche. That is, correlation is not necessarily an indication of causality, and the important functional changes remain unclear.

Future research must use the latest technologies that allow the characterization of the structure of ruminal microbiomes and their relationships to function (Firkins et al., 2008). We must identify microbiomes than can either effectively break down fiber while providing less hydrogen for methanogenesis, or microbiomes that can capture the hydrogen produced into fermentation end-products that supply nutrients to the cow. As a research tool, microbial microarrays provide a holistic approach to studying rumen ecology and high throughput capabilities. Microarrays are also a useful tool to study perturbations in rumen function caused by dietary manipulation including feeding of rumen modifiers (Area 2; compounds that alter rumen function). For example, van Zijderveld et al. (2011) discussed why combinations of rumen modifiers offer promise to reduce methane production; however, lack of knowledge in monitoring lipid-metabolizing microbes based on their unique fatty acid patterns in milk still prevented their ability to decrease methane per unit of milk fat produced.

The Advisory Group particularly emphasized the need for more research on protozoa as a reflection of their large role in methanogenesis, nitrogen recycling in the rumen, and effects on rumen pH. The protozoa are seen as a key in feed digestibility, energy and protein availability to the cow, and ultimately dairy cow performance. The panel also thought that research on acetogenic bacteria as an alternative hydrogen sink may provide opportunities. The Advisory Group identified lack of information on volatile fatty acid (VFA) production rates resulting from rumen fermentation as a specific weak area in our current knowledge (Figure 4; Firkins et al., 2006). Information on VFA concentrations and molar proportions in the rumen fluid is not adequate to predict energy availability to the cow or the amount of methane generated in the fermentation because established patterns of production can be influenced by interconversion or anabolic usage of VFA for microbial growth. Any research on rumen ecology needs to be integrated to the whole animal level to evaluate the impact on whole animal performance.

Mathematical models are research tools that provide integration of knowledge across various functional levels (i.e. rumen function, whole animal, and farm levels) and can be viewed as part of larger models and experimental approaches (Area 8, Figure 9). Models of rumen function could help us evaluate outputs from indicator species of rumen microbes that are associated strongly with key metabolic measurements related to desirable fermentation (i.e., high digestibility relative to the amount of methane produced), and also to other whole-cow measurements such as production of milk or milk components. Thermodynamics and the relationships between hydrogen balance, VFA production versus inter-conversion, and methane production can be incorporated into rumen function and larger system models to help explain the variation among measurements, and thus improve their feasibility for groups of animals. More robust models would help users run simulations to know when different feeding strategies or rumen modifiers are more efficacious or when other strategies should be employed to improve cost:benefit ratio and producer confidence in new strategies (whole animal and farm levels, Area 8).

Area 2. Rumen function and modifiers

Summary: While *in vitro* and *in vivo* studies involving rumen modifiers have shown dramatic methane reductions of 30 to 40%, the consensus among scientists in the field of ruminant nutrition is these compounds have the potential to consistently reduce enteric methane emissions by 5 to 10%. These modifiers may or may not enhance milk production, and more research is needed to make sure there are no downsides to adoption (i.e. reduced feed intake or changes in yield of milk or milk components). A few

downsides might prevent future adoption of other improved strategies by dairy producers. Finally, effective modifiers should also increase feed efficiency, which would improve growth of replacement heifers and lactation performance in cows (Area 3).

This area is the development and extension of the previous discussion on rumen microbial genomics and ecology (Area 1) into practices and compounds that can be used to reduce methane emissions and increase the efficiency of dairy production. Research and development of rumen function modifiers that alter fermentation pathways, provide alternative hydrogen sinks, change populations of microbial species that produce methane (methanogens), and improve microbial growth and efficiency are all approaches that have potential to reduce methane emissions from ruminant livestock (Table 1; Joblin, 1999; Boadi et al., 2004; Patra and Saxena, 2009). Whenever possible, these strategies need to be incorporated using proven approaches to improve feed efficiency of animals (Beauchemin et al., 2008).

The use of compounds that could serve as alternative hydrogen sinks is an approach that can potentially reduce methane, and represents a research area that should be continued (McAllister and Newbold, 2008). Propionate, one of the VFA produced in rumen fermentation is a natural hydrogen sink. Propionate production can be enhanced by increasing the proportion of starch in a ration and by replacing sugars with starch (Monteny et al., 2006). Propionate precursors such as malate, fumarate, and acrylate can also reduce methane production (Table 1; Martin et al., 2010; Moss et al., 2000). Also, the use of naturally occurring compounds such as fats, essential oils, saponins, and tannins to modify rumen fermentation and reduce methane emissions has good potential (Table 1; Calsamiglia et al., 2007; Beauchemin et al., 2008; Eugene et al., 2008; Benchaar, 2010; Chaudry and Khan, 2010; Martin et al., 2010). However, some of these compounds compromise fiber digestion and reduce dry matter intake (Beauchemin et al., 2008; Hollmann and Beede, 2010), and they can also result in the rumen production of biohydrogenation intermediates that can cause milk fat depression (Bauman & Griinari, 2003). Also, concentrations of these compounds that would be effective in reducing methane may not be practical to feed.

Ionophores, including monensin, have been long known to increase rumen propionate concentrations and reduce methane production (Table 1; Odongo et al., 2007) in *in vitro* incubations and during short term feeding. However, it is not clear whether the reduction is persistent (Guan et al., 2006; Hook et al., 2009). Potential disadvantages of these mitigation approaches must be weighed against the potential benefits of methane emission reductions, and alternative strategies should be viewed within their larger context of opportunities such as improved feed efficiency (Beauchemin et al., 2008). For example, beef cattle with high feed efficiency were correlated with certain species of bacteria (Guan et al., 2008) and methanogens (Zhou et al., 2009). Also, methane emission reductions that concurrently decrease milk yield per cow are not desirable, because more cows will be required to maintain milk supplies, with more total methane being emitted by the U.S. dairy industry.

Quantitative measurements, including methane production (Area 7), are critical to advancing this area. Continued evaluation of potential rumen modifiers is important, particularly investigations into the synergistic effects of multiple compounds and the persistency of the effects. All research on rumen modifiers needs to be integrated to the whole animal level to evaluate the long-term impact on animal performance (production of milk solids); *in vitro* studies as a stand-alone approach are not adequate to fully evaluate the potential modifiers.

Table 1. Rumen modifiers that lower enteric methane production per unit animal product (\uparrow = increases; \downarrow = decreases). Based on reviews by Boadi et al., 2004, Beauchemin et al., 2008, Martin et al., 2010, and kindly provided by Drs. Sander Van Zijderveld, Hink Perdok, and James Aldrich, Promivi.

Strategy	Mode of action	Comments
Defaunation	Protozoa \downarrow ; $H_2 \downarrow$; archaea \downarrow	Microbial adaptation?
Saponins, e.g. <i>Yucca schidigera</i>	Protozoa \downarrow ; $H_2 \downarrow$; archaea \downarrow	Microbial adaptation?
Tannins, e.g. sainfoin	Protozoa & archaea \downarrow	Microbial adaptation?
More concentrate & starch (or algae) in diet	Propionate \uparrow ; H_2 sink	Competes with monogastrics
PUFA, e.g. linseed C18:3 fishoil, EPA, DHA	Cellulolysis \downarrow ; small H_2 sink;	Dose dependent; dry matter intake (DMI) may drop
Saturated fatty acids, e.g. C12:0; C14:0	Archaea inhibition	DMI \downarrow
Organic acids e.g. fumaric, malic	H_2 sink	Small effect; expensive
Reduction of nitrate and sulfate	H_2 sink	Persistent; toxic intermediates
Ionophores, e.g. Monensin	Propionate \uparrow ; H_2 sink	Microbial adaptation
Enzymes, yeasts and probiotics	Propionate \uparrow ; H_2 sink, pH	Varying results
Other plant extracts, e.g. garlic, eucalyptus	Archaea inhibition	Microbial adaptation?
Immunization against archaea	Archaea inhibition	More research required
Bacteriocins & archaeal viruses	Archaea inhibition	More research required
Short chain nitrocompounds	Archae inhibition; H_2 sink	More research required

Area 3. Enhancing feed quality and feed ingredient usage to improve feed efficiency

Summary: Improved quantitative understanding of nutrient interrelationships will lead to better use of feed nutrients for milk synthesis, improved animal performance, increased feed efficiency, and reduced nutrient waste, including reduced ammonia and methane emissions into the environment. Improvements in dairy cattle nutrition and feeding can easily increase feed efficiency from 1.4 to 1.5 lbs milk/lb feed, with a corresponding 6 – 8% decrease in methane per lb. of milk.

Improving feed efficiency (yield of milk components per unit of feed intake) is well established as one of the best ways to reduce methane production in individual animals (IPCC, 1990; Figure 6). Feed ingredients provide the substrates for microbial fermentation, and differences in feed quality alter the amount of energy extracted by the microbes and the pattern of VFA and methane produced. These alterations can impact energy and protein availability to the cow and, ultimately, the efficiency at which the feed nutrients are used for productive functions including growth and milk synthesis (Figure 6; NRC, 2001). Nutrition advisors and dairy producers have known for over a century that more digestible feeds improve lactation performance, reduce methane production, and increase feed efficiency (Armsby, 1882). However, there are still opportunities remaining for a better understanding of nutrient requirements, feed digestibility, and nutrient supply for milk synthesis (NRC, 2001).

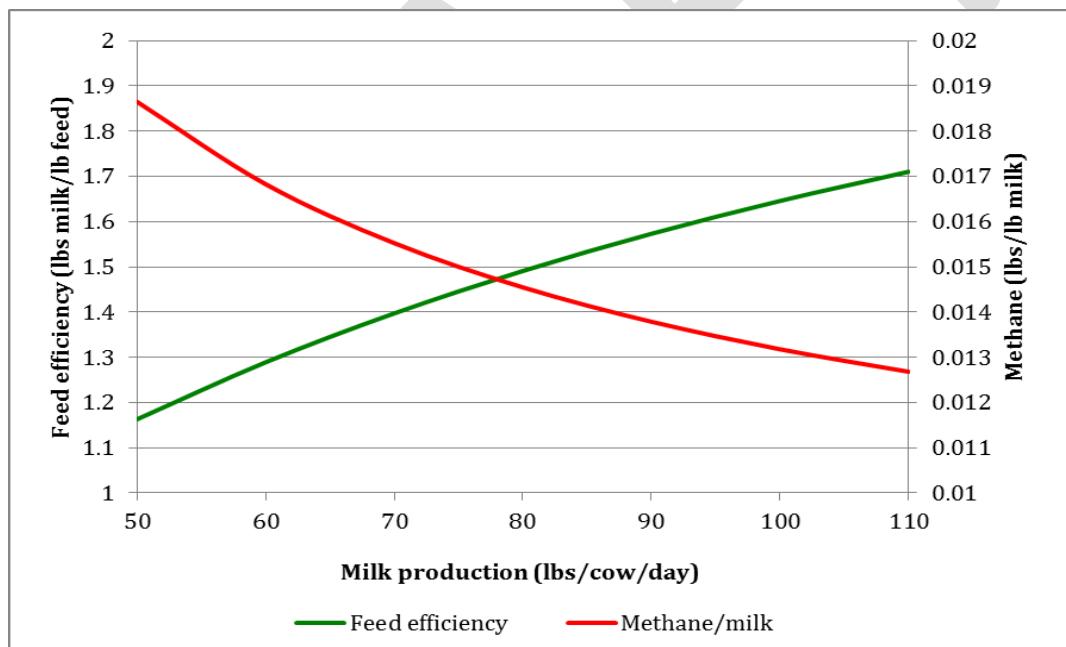


Figure 6. Incremental improvements in feed efficiency (lbs. energy-corrected milk/lb. feed) lead to corresponding reductions in methane emissions (lb/lb milk). Currently in the U.S., on average cows produce 72 lbs. energy-corrected milk/day while consuming 50.1 lbs. feed, with a feed efficiency of 1.44.

Feed efficiency has been identified by the Advisory Group as an area in dairy nutrition with a large knowledge gap, with high potential value for improving dairy profitability and reducing methane emissions per unit of product. The Advisory Group believes that feed efficiency needs to be examined in growing heifers and lactating cows. Research focused on the nutrition of groups of cows vs. individuals will substantially advance knowledge in the field and lead to

identification of more opportunities to improve feed efficiency and reduce methane emissions. In heifer nutrition, limit feeding was identified as having excellent potential to reduce methane emissions, through the two-pronged approach of reduced dry matter intake combined with the use of more digestible feeds (Hoffman et al., 2007; Zanton and Heinrichs 2007).

As discussed previously, ruminant animals, including dairy cattle, add substantial value to the human food supply through their innate ability to convert the nutrients in human-inedible forages and by-products to human-edible products such as meat, milk, cheese, yogurt, butter, etc. By-products (also known as co-products) are waste streams associated with processing of grains and oilseeds for human consumption, rejected human food, cotton processing, and biofuel generation (ethanol and biodiesel). Examples include: distillers' and brewers' grains, bakery by-product, oilseed meals (soybean, canola, sunflower, safflower, etc.), cottonseed, wheat bran, wheat middlings, hominy, corn gluten feed and meal, beet and citrus pulp. Feeding by-products to cattle prevents them from reaching landfills where natural decomposition would reduce them completely to carbon dioxide and methane. In addition, the ethanol and biodiesel industries would not be economically viable if their by-products were not marketed to and consumed by livestock. Therefore, understanding the impacts of by-product feeding on feed efficiency in dairy cattle is desirable.

A significant amount of methane emissions is associated with the ruminal fermentation of plant cell wall constituents of forages and by-products. Improving forage quality can improve diet digestibility, and increase dry matter intake and milk production (Weiss, 1993; Johnson and Johnson, 1995). Forage quality can be improved through plant breeding, including genetically-modified plants, and improved harvesting and storage conditions (Vogel and Sleper, 1994; Rotz and Muck, 1994; Berger et al., 1994). Improvements in forage quality that translate into improved digestibility also result in increased microbial growth, increased energy availability to the cow, increased milk production, and improved feed efficiency (Beauchemin 1991; Beauchemin et al., 2003). Methods of feed processing that increase diet digestibility will also improve feed efficiency (Campling, 1991; Firkins et al., 2001). These methods include: grinding, rolling, and steam-flaking grains; kernel processing of corn silage, addition of hydrolytic enzymes, and chemical treatment with alkali, ammonia, or aldehydes (Bal et al., 2000; Firkins et al., 2001). Since all these methods require energy inputs, the potential benefits must be considered in relation to the energetic cost of processing.

As part of feed efficiency, a quantitative understanding of the interrelationships between rumen function and nutrient availability to the cow is critical to improving predictions of milk yield performance and nutrient utilization (Baldwin, 1995; Hanigan et al., 2006; Kebreab et al., 2009). The biochemical pathways of nutrient metabolism have been known for more than 50 years. However, the metabolic flexibility that exists in these pathways has not been quantified, nor has the impact of genetic selection in dairy cattle on the quantitative use of nutrients been fully accounted for (Hanigan et al., 2006). The importance of high quality forage for efficient production of milk has been known for decades but in light of new diet formulation strategies (e.g., formulating based on fiber digestion kinetics) and ever increasing dry matter intake and milk production, optimal forage quality for dairy cows needs to be re-examined. Improving the digestibility of concentrate feeds via genetics, physical or chemical processing, and improved diet formulation also needs to be re-evaluated with today's high producing cows. Nutrition and feeding management is a very broad area, with many opportunities for mitigating methane emissions. Overall, continued research that leads to refinements and improvements in predicting animal performance will increase feed efficiency and reduce methane emissions per unit of milk produced.

Area 4. Genetic approaches to increase individual cow productivity

Summary: Genetic selection for milk yield has increased milk yields at a steady rate of 200 lbs. per cow per lactation over the past 25 years. This progress rate is expected to continue and will contribute to improved animal performance and reduced methane emissions per unit of energy-corrected milk of 4 to 5%. Additional improvements in feed efficiency, milk yield, and reduction in methane emissions could be achieved through additional selection based on residual feed intake. Also, selection for increased life-time production, whether through disease resistance, improved reproduction, and heat stress tolerance, in combination with supportive management practices (Areas 5 and 6) will further reduce methane emissions per unit of milk.

Tremendous progress in genetic selection of dairy cattle has been made over the past 60 years, and in combination with improvements in animal management has resulted in a 400% increase in milk yields (Figure 7). This increase in milk yield is paralleled by a corresponding 64% reduction in the U.S. dairy cattle population and 57% reduction in methane emitted per unit of product (Capper et al., 2009). Although remarkable gains have been made in milk yield through genetic selection, there is no indication that the genetic potential for milk yield is approaching a maximum. Variation is still large (± 5500 lbs. per lactation), indicating that substantial heterogeneity still exists in the population to permit selection. Also, there are huge gaps between breed averages and the records of the highest producing herds and cows in each breed (i.e. the average Holstein cow produces 23,000 lbs. milk per lactation while the record is 72,170 lbs.).

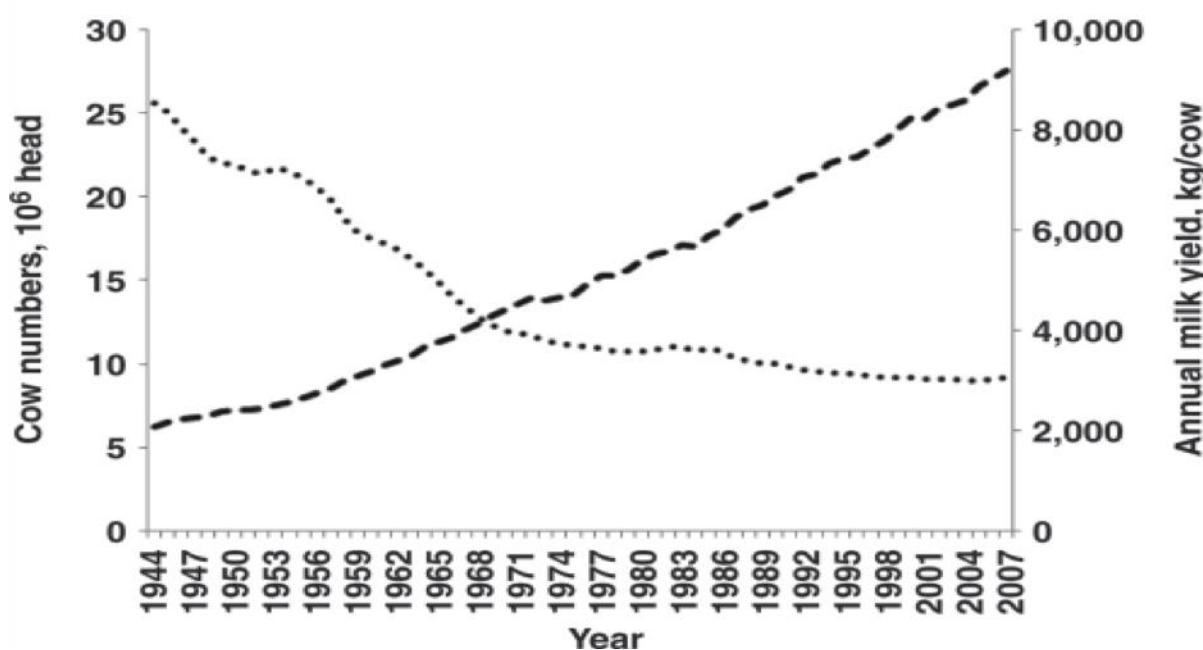


Figure 7. Changes in U.S. dairy cow numbers (dotted line) and individual cow milk yields (dashed line) over the past 60 years. From Capper et al., 2009.

On an individual cow basis, methane per unit of milk can be reduced by two different approaches. The first is to increase milk yield per cow with correspondingly smaller increases in dry matter intake, which dilutes the maintenance energy costs of the cow and increases energetic efficiency. The second is to reduce body size without reducing yields of milk and milk components, which also has the effect of increasing energetic efficiency, but by decreasing the energy requirements of the animal. Both approaches are based on the fact that maintenance energy costs of cows are a fixed cost and a function of their body size. Because methane production is proportional to the energy intake of the animal, reducing maintenance energy costs and energy intake while maintaining milk yield would decrease enteric methane, both on a per cow per day basis and a per lb. of milk basis.

Genetic selection over the past six decades has been based largely on the first approach above, with increasing yields of milk and milk fat. Selection for yields of milk protein has been implemented over the past two decades in the U.S. dairy industry. While the second approach above is theoretically possible, it has not been widely pursued in the U.S. dairy industry. It must be realized that reducing body size while maintaining milk production is limited due to the amount of food that can be consumed by smaller animals. Although it is often speculated in the dairy industry that Jersey cows are more energetically efficient than Holsteins due to their smaller body sizes and higher content of milk solids, the research literature is mixed. Research on energy metabolism of mature Jersey and Holstein cows did not show any breed differences for maintenance and production requirements per unit of metabolic body weight ($BW^{0.75}$; Tyrell et al., 1991). Consequently, methane production per unit of milk was not different between the two breeds. In recent cross-breeding experiments conducted at Virginia Tech University, first-lactation Jersey cows produced more energy-corrected milk per unit of metabolic body weight than Holsteins and Jersey-Holstein F1 crosses (Olson et al., 2010). However, it appears that the Jerseys were more physiologically mature at calving than the Holsteins and did not use as much energy in support of growth during the first lactation. Whether this breed difference in energetic efficiency would continue into the second and greater lactations is unknown and would require further study.

An alternative approach would be to genetically select for those cows that are more efficient in using feed nutrients to synthesize milk components. Residual feed intake (RFI) has been increasingly used in non-ruminant and beef production systems as a tool to assess and genetically select for feed efficiency (Herd and Arthur, 2009). RFI was originally defined by Koch et al. (1963) as the difference between measured feed intake and feed intake predicted from maintenance and growth estimates for an individual animal. Greater efficiency is denoted by a negative RFI value and lower efficiency by a positive RFI value. RFI is moderately heritable in beef cattle (Koch et al. 1963) and follows a normal distribution improving its utility for conventional genetic selection compared with feed efficiency (lb. energy-corrected milk/lb. dry matter intake) which is usually not normally distributed. The genetic and physiological basis of RFI is sound (Herd and Arthur, 2009). In dairy cattle, RFI may be computed as the deviation in feed intake of an individual cow from that predicted by an equation such as that derived by the NRC Nutrient Requirements of Dairy Cattle (2001). RFI offers considerable potential for improvement in productivity through genetic selection compared with ratio-based measures of feed efficiency (St-Pierre & Thraen, 1999).

Lastly, genetic approaches that increase life-time production, including those that improve health, disease resistance, reproduction, and tolerance to heat stress will lead to improvements in individual life-time and herd productivity (Areas 5 and 6) and indirectly reduce methane

emissions per unit of milk. Incidences of common diseases in dairy cattle have low to moderate heritabilities ($h^2 = 0.05$ to 0.25 ; Uribe et al., 1995; Zwald et al., 2004) and are positively associated with selection for increased milk production (Rauw et al., 1998). It has been shown that tolerance to heat stress is also heritable (Ravagnolo and Misztal, 2000), and these authors and others have hypothesized that the threshold at which cows begin experiencing heat stress is lower in higher-producing dairy cows. During the past decade, selection indexes for dairy cattle have been modified to include reproductive traits, susceptibility to mastitis, and productive life (Lifetime Net Merit Index; Van Raden et al., 2004), all of which will increase the efficiency of milk production and further reduce methane emissions.

Area 5. Management practices to increase individual cow productivity

Summary: Management strategies targeted at improving animal health, reproduction and performance, and ameliorating heat stress through the transition period from pregnancy to lactation will improve individual cow and herd productivity. Applications of management practices in all three sub-areas can lead to increases in productivity in combination with reductions in replacement animals needed (Area 6). These improvements are conservatively estimated to reduce methane emissions per lb. of fluid milk at the whole-herd level by 6 to 18%, assuming that the improvements are not likely to be additive. Nor do they include improvements in life-time productivity, as a more detailed model would be required for those predictions. However, at this time, it is not widely recognized in the U.S. by either dairy owners or dairy professionals that improvements in reproduction, heat abatement, and transition cow health and performance can have substantial impacts on methane emissions. Such improvements represent a win-win situation; they will increase dairy profitability while reducing methane emissions. Although it is easy to identify the problems associated with each of these areas, significant research is needed to better understand the underlying causes of the problems and identify solutions that will lead to better management practices.

In the past 60 years, milk yields have increased 400% (Figure 7). Approximately 50 to 55% of the increase has been achieved by genetic selection, and the remainder through improvements in management practices (Hansen, 2000; Van Raden, 2004; Shook, 2006). Animals cannot reach their full genetic potential if factors in their environment are limiting. Currently in the U.S., there is a wide range in milk yields that reflects the variation in genetic potential and the variation in environment, which is altered by management practices (Figure 8). Herd production averages range from 50% to 150%+ of the average, with individual animals recorded at 350% of the average.

Management practices that enhance the ability of individual cows to increase milk yields and reach their genetic potential will reduce the amount of methane produced per unit of milk on the whole herd. These management approaches may include practices to reduce non-voluntary culling and diseases, facility and equipment designs to improve the cows' environment, and use of performance enhancing technologies (i.e. recombinant bovine somatotropin) as well as improvements in nutrition and feed delivery. All of these approaches have potential to improve profitability as well as decrease methane emissions. The Advisory Group identified three management sub-areas as very important: reproduction, heat stress, and transition cow health. While these sub-areas impact individual cow productivity, in most commercial settings each sub-area will require management changes that employ a whole-herd approach.

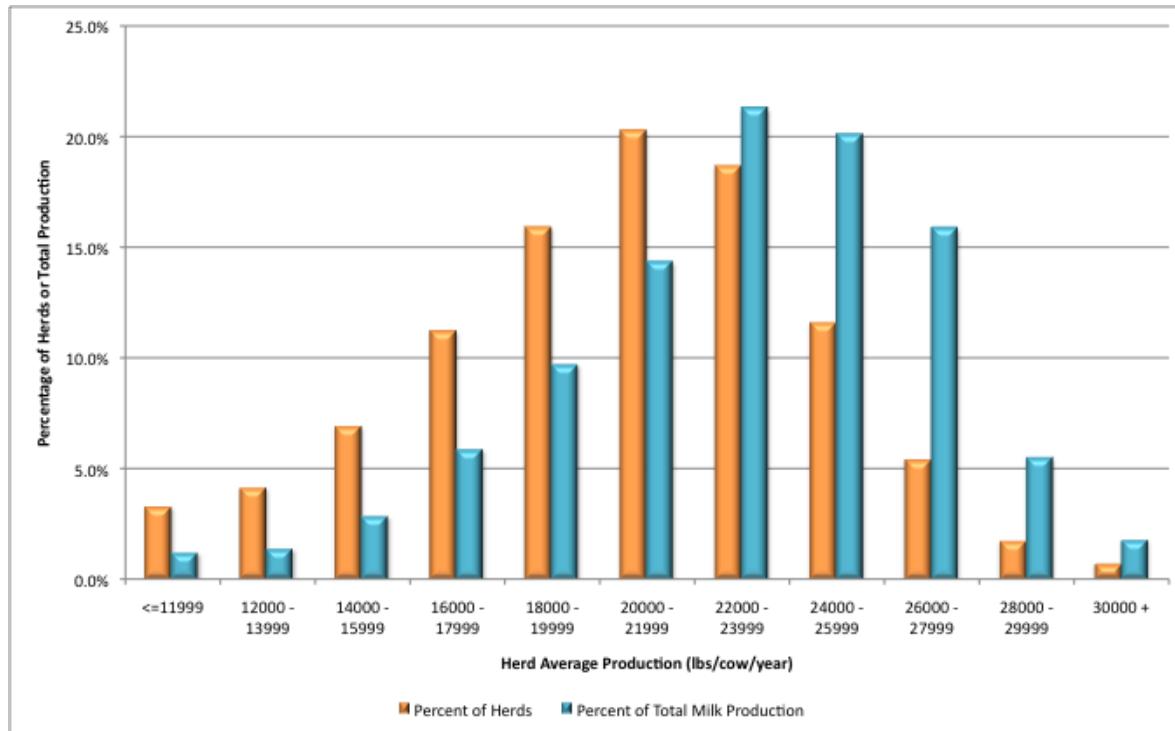


Figure 8. Herd milk production (orange bars) in the U.S. dairy industry varies widely, and is a reflection of the genetic potential of the cows and management practices that impact their environment. Of the total milk produced in 2010 (blue bars), the top 50% of the herds produce more than 75% of the milk.

Reproduction is critical in all domestic livestock species. For dairy cattle, it is obligatory because pregnancy is part of the lactation cycle. In dairy cattle, gestation and lactation overlap; cows ideally become pregnant 3 to 4 months after the previous calving and beginning of the current lactation. Reproductive efficiency also impacts dairy farm profitability (De Vries, 2006), because cows spend more time in the highest yielding part of their lactations and have longer productive lifetimes in well-managed reproduction programs. Also, less replacement animals are needed in herds with better reproduction rates.

Fertility has declined with the advent of artificial insemination and genetic selection in all the major dairy breeds in the U.S., and is most pronounced in Holsteins (Lucy, 2001). The decline in fertility has often been associated with the selection for increasing milk yield (Hansen, 2000; Lucy, 2001); however, fertility has a low heritability and a small negative correlation with milk yield ($h^2 < 0.04$ and $r = -0.10$; Hansen, 2000; Van Raden et al., 2003). Notably, the fertility decline has not been observed in virgin heifers, indicating that the problem is associated with lactation and milk production. The decline in fertility has also been associated with increasing herd sizes (Lucy, 2001). However, more recent data from Canada showed that higher producing herds had significantly higher pregnancy rates, suggesting that management efforts to support high milk yields can also result in good reproduction (Campbell et al., 2009). Many management factors may be responsible for the declines in reproductive efficiency in U.S. dairy cattle observed over the past 60 years. Currently, approximately 19% of culling decisions are for reproductive reasons (Hadley et al., 2006). Research that leads to improvements in estrus detection, estrus synchronization, prevention of early embryonic death, heat stress abatement, and transition cow health would result in improvements in reproduction, and reduce the number

of cows culled due to poor reproduction. In turn, reduced culling reduces the requirement for replacement animals and can reduce whole-herd methane emissions (Area 6). A 5% reduction in culling due to poor reproduction is estimated to reduce whole-herd methane emissions by 3.5% (Knapp, unpublished observations). This estimate does not include the improvement in life-time productivity that accompanies improvements in reproduction. Additionally, dairy profitability is improved by reducing days open (not pregnant) that are beyond the optimum (Gronendaal et al., 2004; De Vries, 2006). The economic value of reduced days open is not only a function of the mean days open but also of its variance (St-Pierre, personal communication).

Heat stress impacts the performance of dairy cattle as well as other livestock, and has been estimated to result in annual economic losses of \$897 million to the U.S. dairy industry (St-Pierre et al., 2004). With increases in milk prices and electricity costs, economic losses could be 25% higher today (St-Pierre, personal communication). Animal responses to heat stress include reduced dry matter intake, decreased average daily gain, decreased milk yield, and decreased fertility and poor reproduction (Kadzere et al., 2002; Hansen, 2007). Heat stress also contributes to increased culling and death losses (St-Pierre et al., 2004). During heat stress, milk production is decreased more than dry matter intake, which increases methane/unit of energy-corrected milk (Rhoads et al., 2009). It may not be the extent of heat stress alone that affects animals, but also the duration of the heat stress (Hubbard et al., 1999, St-Pierre et al., 2004). This is supported by anecdotal evidence from the dairy industry, where it is commonly observed that adequate night cooling reduces the impact of heat stress during multiple-day periods of elevated temperature and humidity.

It is also hypothesized that the minimum threshold where animals begin experiencing heat stress is a function of production level of the animals (Bouraoui et al., 2002; Kadzere et al., 2002; St-Pierre et al., 2004; Zimbelman, 2008). Endogenous heat production increases with the increased dry matter intakes and metabolism associated with increased milk yields (Kadzere et al., 2002). At the same ambient temperature, a higher-producing dairy cow will have to dissipate more heat to the environment than a lower-producing cow of the same size. Ragnovolo & Misztal (2000) found a negative genetic correlation ($r=-0.36$) between the heritability for milk yield and heat tolerance. This finding suggests that as U.S. dairy cattle have been selected for improved milk yields, their tolerance to heat stress has decreased. Genetic selection and management practices that improve tolerance to heat stress will improve cow productivity and dairy profitability, reduce mortality, and reduce methane/unit of energy-corrected milk. A 25% improvement in heat stress tolerance is estimated to reduce culling by 2.5%, deaths by 0.5%, and milk production losses by 2200 lbs./cow/year, with a net reduction in methane/lb. of fluid milk of 9% (Knapp & St-Pierre, unpublished observations). An additional environmental consideration is that current management approaches for heat stress abatement in the U.S. use large amounts of water to enhance evaporative cooling and require electricity to pump the water and run fans. Strategies that reduce or eliminate water and fan use in abatement may have substantial value in the future.

One of the most challenging areas in dairy cattle management is the transition period from gestation to lactation that occurs around calving. The highest incidence of metabolic and infectious diseases is seen in the first 60 days post-calving, with corresponding high rates of culling, death, and loss of life-time production (De Vries, 2004b; Hadley et al., 2006; Overton and Fetrow, 2008). Across all stages of lactation, culling for disease and lameness accounts for 20% of all culling (Godden et al., 2003; Hadley et al., 2006). Given the magnitude of losses incurred during the transition period, research on the management and development of new

approaches should be a high priority for the industry. Many of the diseases that occur during the transition period are interrelated, and a cow that experiences one disease is more likely to experience additional diseases (Curtis et al., 1985; Burhans et al., 2003). Cows are more susceptible to infectious disease during the transition period as their immune responses are blunted or reduced during the time around calving (Overton and Waldron, 2004). Also, cows that experience disease early in the lactation are more likely to have poor production and poor reproduction, with increased days open and increased services per conception (Schrick et al., 2001). Additionally during the transition period, cows are more sensitive to heat stress, resulting in poor milk production and poor reproduction (De Vries, 2004). Management improvements that decrease the incidence of infectious disease and metabolic disorders during the transition period will decrease involuntary culling and death loss, and increase individual cow productivity. A 5% reduction in culling for disease during this period in combination with increased milk yields of 2000 lbs./cow/year is estimated to reduce whole-herd methane emissions by 12% (methane lbs/lb. of energy-corrected milk; Knapp, unpublished observations).

Area 6. Management of herd structure to reduce number of cow-days of non-productive animals (replacement heifers and dry cows)

Summary: Genetic and management approaches that reduce the need for replacement animals and increase the life-time production of cows will result in significant reductions of methane/lb. of energy-corrected milk produced in herds. Research initiatives that address the diversity of underlying factors that contribute to herd reproduction, health, and performance will lead to improved genetic selection and management practices. Wide-spread adoption of improved practices can lead to significant reductions in methane emissions per unit of energy-corrected milk as well as increases in dairy profitability.

Management of herd structures to reduce the number of non-productive animals is an immediately effective approach to reduce methane per unit of milk and increase dairy profitability. The number of dry cows in a herd is largely a reflection of the effectiveness of the reproduction program used. Good reproduction management will result in an optimal dry period length for individual cows that is a balance between having a minimum dry period that allows mammary tissue to involute and regenerate in order to achieve good production in the following lactation vs. having too long a period with no production. Effective reproduction programs will also effectively increase milk per cow by having cows spend more of their productive days in the higher portions of the lactation production cycle.

With replacement heifers, the number needed is a function of culling of the older cows in the lactating herd, age at first calving, heifer mortality and culling, and individual goals for expansion. Current culling levels in the U.S. average 30 to 35%, and are primarily involuntary, largely attributable to disease and poor reproduction (Area 5; Hadley et al., 2006). Reducing age at first calving for properly developed heifers will reduce the energy requirements during the growing period, which is a non-milk productive period which contributes substantially to the maintenance energy required by the herd. Decreasing mortality and morbidity rates also has a significant effect on methane reduction because animals that die or are culled before their first lactation represent a significant use of energy and resources without any usable food product being produced. Lower culling levels, reduced age at first calving, and reduced heifer mortality would reduce the number of replacement heifers needed (Figure 9). This would be accompanied by a corresponding, but smaller, decrease in methane emissions by the whole herd.

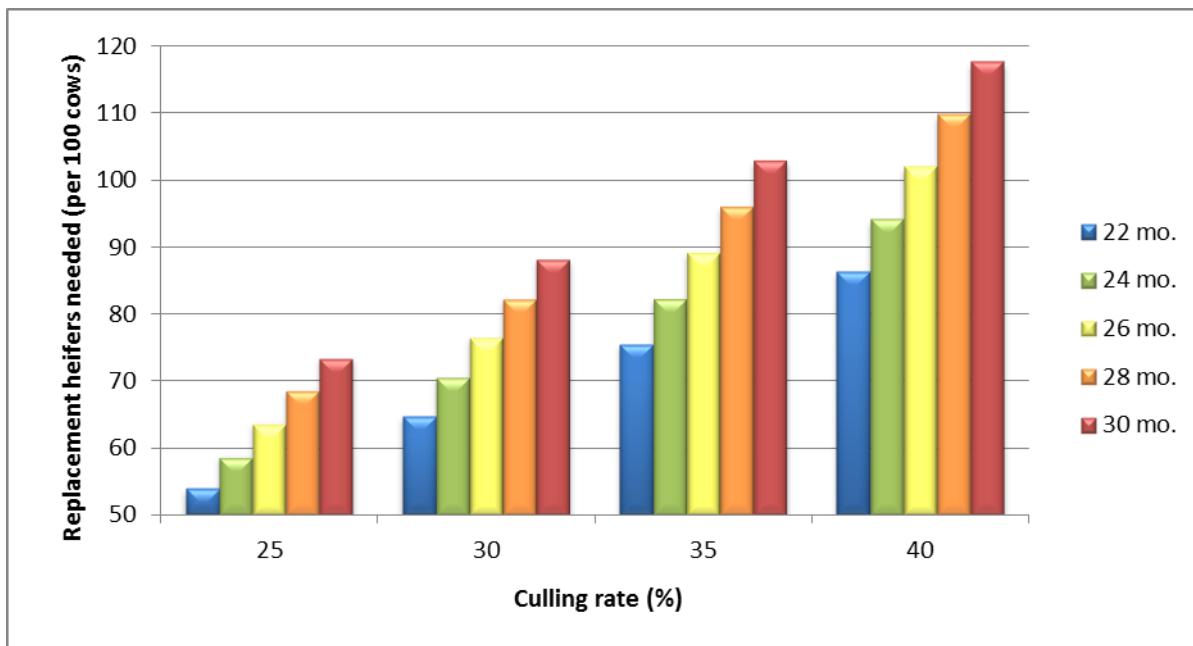


Figure 9. Impact of age at first calving and culling rate on number of replacement heifers needed to maintain a static herd size, with assumed heifer mortality and culling of 15%.

For example, reducing age at first calving from 26 to 24 months and the culling rate from 35% to 30% will reduce the number of heifers needed as replacements by 20% (Figure 9) and whole-herd methane emissions by 5.5%. However, culling levels that are too low compromise genetic progress from generation to generation, and heifers calving too young (<21 months) result in lower life-time production (Gill & Allaire, 1976). Reducing heifer mortality and culling results in an equal reduction in the proportion of heifers needed as replacements, i.e. a 5% reduction in mortality and culling translates into 5% less heifers needed, and provides a substantial opportunity for the dairy industry to reduce methane emissions.

Area 7. Development and refinement of methane measurement techniques

Summary: Existing enteric methane measurement techniques, including respiration chambers, open-circuit respiratory devices, and SF₆ dilution, require expensive equipment, are labor-intensive to operate, and are limited in use to small number of animals. Also, measurements made in one system may not be directly comparable to another system. Improved techniques that allow measurement from larger groups of animals in typical production settings that provide more repeatable, accurate, and precise measurements, and that are less expensive would be desirable to augment several of the research areas discussed above. In particular, development of devices and equipment that enable measurement of enteric methane emissions under field conditions will be invaluable to future research.

Currently, there are two established techniques for measuring enteric methane production from ruminant animals: respiration chamber and the sulfur hexafluoride (SF₆) tracer gas techniques. The use of respiration chambers is the 'gold standard' although the technique is expensive, cannot be used on a large number of animals (particularly dairy cows), and has been criticized as an 'unnatural' environment, especially when compared to pasture conditions. However, to what extent the confinement of the animal in a respiration chamber is affecting its methane

production, compared to tie-stall, free-stall, or pasture environment is unknown. The SF6 tracer method was developed by a team from Washington State University led by Dr. K. Johnson (Johnson et al., 1994) for measuring enteric methane production in range cattle. The technique is easy to use; its biggest advantage being that the animal is not restricted and is in its natural environment, in contact with its peers. The method has been mostly criticized for producing larger variability than the respiratory chamber technique (Pinares-Patiño and Clark, 2008; Clark, 2010). Clark (2010), for example, found a good agreement in mean methane emission measurements for animal groups between SF6 and the chamber methods. Variability, however, was about twice as large for the SF6 method and the correlation between emission values obtained from individual animals and repeatability in the estimated rates was low. The SF6 release rate can be a major factor affecting methane emission data with this technique (Martin et al., 2010). Extended sample collection periods may help reduce this variability (Gere et al., 2010; Lassey et al., 2010). A shortcoming of this method is that SF6 is a very potent greenhouse gas [23,900 times the global warming potential (GWP) of carbon dioxide] and is already banned in several countries.

New techniques for measuring enteric methane emission are emerging. An open respiratory device has been commercially developed that enables measurement of methane emissions under field conditions. The device is based on random and repeated sampling of breath air exhaled by the animal into a headstall unit and use of a tracer gas with considerably lower GWP than SF6 (Zimmerman et al., 2011). Simulation of respiration chamber data with the headstall device showed good repeatability and low measurement error (A.N. Hristov, unpublished observations). The device is producing results that are consistent with literature and established values. Future work needs be completed to directly compare measurements from the device against established techniques. Madsen et al. (2010) recently reported an indirect method for measuring enteric methane emission based on methane-carbon dioxide ratios and estimation of total carbon dioxide production. The technique is simple, fast, and inexpensive. Another approach takes advantage of miniaturized infra-red sensors housed inside a diffusion cell coupled with wireless data transfer as *in situ* probes that can be placed in the rumen of animals (Laporte-Uribe and Gibbs, 2009). These probes have the potential to provide continuous monitoring of the rumen environment with low labor input. The simple data acquisition may enable monitoring of large numbers of animals in their typical environments, including free-stall facilities and while grazing. All of these new approaches must be experimentally verified against the respiration chamber technique.

Area 8. Modelling efforts to quantitatively integrate the knowledge gained in the above areas

Summary: Each of the research areas above represents only a part of enteric methane emissions in dairy cattle and dairy farms. To be able to utilize the information gained in that research, it must be integrated to provide quantitative evaluations of methane emissions per unit of milk production, per animal, per farm, and possibly per geographical region. Because of the complexity, time frame, and number of variables involved, computer modelling and assessment is only the method available to assess methane emissions from entire farm production systems, regions, or countries.

Models have existed in animal agriculture for over forty years, and are the basis of current dairy ration formulation systems (NRC, 2001; Van Amburgh et al., 2008). Other models are being used to evaluate herd health, reproduction, nutrient management, and heifer replacement strategies (Overton, 2001; Rotz et al., 1999; De Vries, 2004). As platforms for evaluating

management strategies, models need to undergo repeated cycles of updating and re-evaluation (Figure 10). A critical component of this cycle is experimentation.

Models are a research tool that will aid in advancing knowledge in animal science and agronomy and a decision-making tool in dairy cattle management. They offer experimenters opportunities for hypothesis testing and the exploration of what-if scenarios that aid in refining experiments (Figure 10). They are useful in providing quantitative assessments of management practices for dairy industry professionals, dairy owners, and policy makers. Furthermore, they aid in identifying the key input factors required for various system models.

Wherever possible, models should include the economics of dairy profitability and the potential for optimization (minimizing methane emissions while improving profitability). Currently, no single software exists that incorporates various dairy farm practices to predict whole-farm methane emissions and the impact of mitigation approaches on profitability. Finally, improved accuracy or reduced variability associated with these predictions should help to integrate all research objectives into a common goal to sustainably reduce enteric methane emissions while maintaining or improving milk production and while improving feed efficiency of U.S. dairy farms.

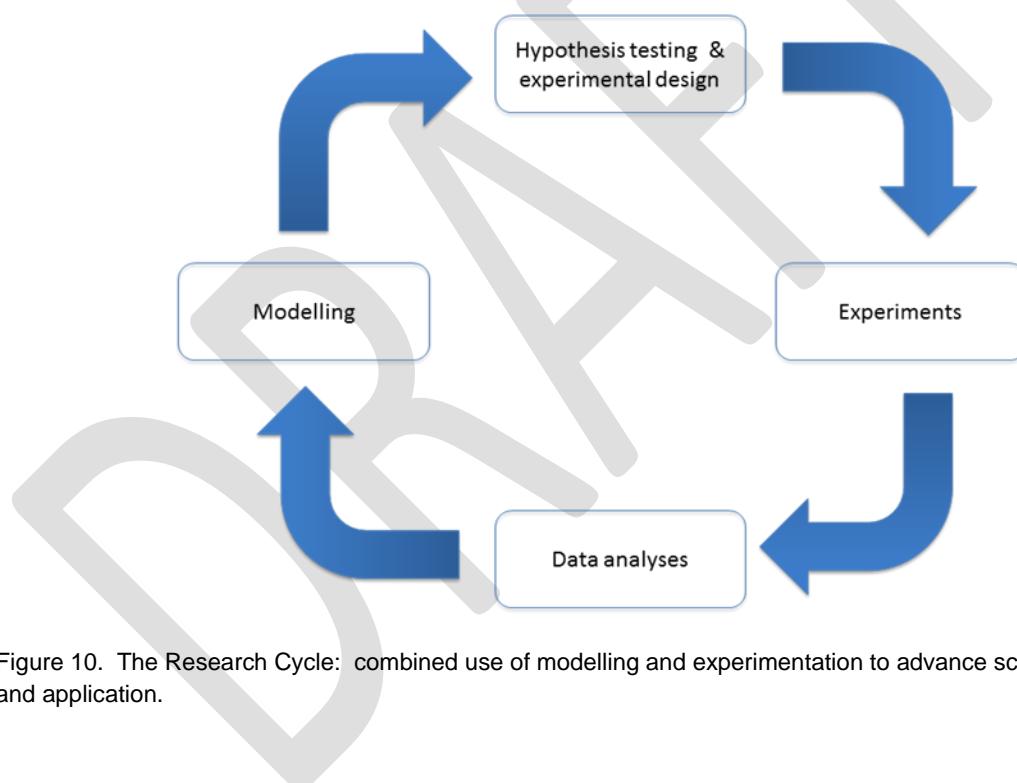


Figure 10. The Research Cycle: combined use of modelling and experimentation to advance scientific knowledge and application.

Several specific areas and issues that need to be addressed in modelling were identified by the Advisory Group:

1. Models are needed to evaluate the interactions among feedstuffs, additives, etc. on enteric methane emissions. Determining the variability or confidence interval around the prediction is important; this will require the addition of stochastic elements to models.
2. Modellers should be encouraged to work together more, as well as teaming up with experimenters. Funding availability continues to limit these opportunities and efforts.
3. Models should be process-based and mechanistic in nature to enhance their potential in identifying and evaluating methane mitigation strategies.
4. Sub-system models need to fit into understanding of larger systems. Progress will be limited if models cannot be integrated into higher levels, i.e. models of rumen function are of limited usefulness if they cannot be integrated with animal metabolism to predict animal performance.
5. Integration/coordination of beef and dairy life-cycle assessments (LCA) is needed to eliminate the double accounting that currently exists in enteric methane emissions. The U.S. dairy industry accounts for approximately 20% of the beef consumed in the U.S. (Knapp, unpublished data). If LCA evaluations are not coordinated between the two industries, both run the risk of overestimating the impact of their production systems on methane emissions and thus underestimating the impact of beneficial changes in one or both systems.

Summary

Historically, scientific reviews and agendas have generally focused on modification of rumen function, feeding management strategies, and genetic selection for growth or milk yield as means to reduce methane emissions in ruminant livestock. However, other opportunities in management practices that improve individual cow health, performance, and reproduction and reduce the number of replacement animals required have significant potential to contribute to the goal of reducing methane/unit of milk (Figure 11).

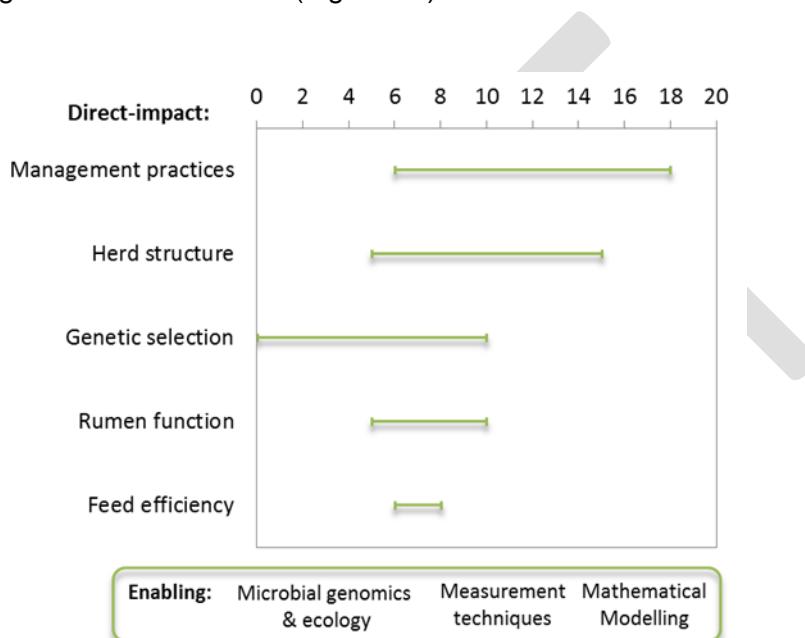


Figure 11. Development of new strategies and technologies through research has the potential to significantly reduce methane per unit of energy-corrected milk in U.S. dairy herds. The impact from microbial genomics and ecology, methane measurement techniques, and mathematical modelling cannot be quantified directly and will be manifested through their enhancement of the other five areas.

It has been very clearly stated that “Improving livestock productivity so that less methane is emitted per unit of product is the most promising and cost effective technique for reducing emissions in the U.S. (EPA, 2005). It has been scientifically demonstrated that historical improvements in dairy production have reduced methane emissions per unit of milk (Capper et al., 2009) and that existing technologies and management practices are also effective (Johnson et al., 1992; Bauman et al., 1992; Garnsworthy et al., 2004; Capper et al., 2008). Implementation of existing technologies and management practices in the U.S. dairy industry along with continued genetic progress in milk yields is expected to result in 10 to 12% reductions of methane emissions per unit of milk over the next decade. To achieve the additional 13 to 15% reduction to reach the overall goal of a 25% reduction requires investment in research to identify and develop new strategies and technologies. Conservative estimates suggest that additional reductions of 15 to 30% can be achieved, dependent upon the development of new strategies and technologies and their adoption by the U.S. dairy industry (Figure 11). The eight research areas that were identified by the Advisory Group are and why they are important are given in the following paragraphs.

Area 1. Rumen microbial genomics and ecology. Increasing our quantitative knowledge and understanding in this area provides the foundation for work on rumen function and modifiers (Area 2) and improvements in feed quality and feed ingredient usage that lead to improved digestibility and feed efficiency (Area 3). Fundamental research in this area will also contribute to improved animal nutrition models and whole-herd models of methane emissions (Area 8). There are no disadvantages of this area with respect to dairy profitability or consumer acceptance.

Area 2. Rumen function and modifiers. Alterations in rumen function by natural or synthetic compounds that reduce methane generation have the potential to reduce enteric methane emissions by 5 to 50%. Significant challenges lay in identifying compounds that have consistent effects on methane formation. These modifiers may or may not enhance milk production, and evaluations must consider these potential disadvantages as well as consumer acceptance. Combinations of modifiers have significant potential, and quantitative evaluations through rumen modelling (Area 8) will strengthen this area. Rumen function can also be improved through feeding practices (Area 3).

Area 3. Enhancing feed quality and feed ingredient usage to improve feed efficiency.

Opportunities in these areas are well known to improve digestibility and feed efficiency. Additional refinements in the quantitative basis of nutrition and feeding management will lead to further improvements in feed efficiency, which directly translate into reduced methane per unit of milk. Computer-based models (Area 8) will strengthen these refinements in quantitative nutrition. Dairy cattle, along with other ruminant livestock, add substantial value to the world's food supply through their ability to convert nutrients in human-inedible feeds to human-edible products. The ability to use these feeds has environmental benefits, for which the dairy industry is not given credit. Improvements in dairy cattle nutrition and feeding can easily result in 6-8% decrease in methane per unit of milk. Also, improvements in nutrition and feeding will be required for animals to fulfill their genetic potential (Area 4) and will complement improvements in management approaches to increase individual cow and herd productivity (Areas 5 and 6). Improvements in nutrition and feeding can also improve dairy profitability, and there are few, if any, downsides to strategies in this area.

Area 4. Genetic approaches to increase individual cow productivity. Incredible progress has been made in the U.S. since the advent of artificial insemination and the ability to use genetic selection for increasing milk and milk fat yields 60 years ago. Continued genetic progress in improving milk yields will lead to reductions of methane per unit of milk in the 5% range. Future genetics need to focus on opportunities in selecting more energy-efficient animals (low residual feed intake), improved tolerance to heat stress and disease, and improved reproduction. Genetic improvements in these areas coupled with improved nutrition and feeding (Area 3) and other management strategies (Areas 5 and 6) have the potential to reduce methane per unit of milk by 20 to 40%. Genetic improvement in milk yields needs to account for the impacts on reproduction and animal health to avoid downsides.

Area 5. Management practices to increase individual cow productivity. Management practices provide the environment in which cows can fulfill their genetic potential. There are very large opportunities for management improvements in reproduction, heat stress tolerance, and transition cow health and performance that can increase the productivity of lactating cows, and reduce methane per unit of milk. However, the underlying factors that contribute to problems in these areas are not well understood, and this is where future research needs to be focused. Improvements in these areas are conservatively estimated to reduce methane

emissions per unit of milk in the range of 3 to 24%, but improvements are not expected to be fully additive, nor does this estimate include increases in life-time productivity. Improvements in these areas will compliment Area 4 (genetic approaches) and would also improve animal well-being, a plus in terms of consumer acceptance, and increase dairy profitability.

Area 6. Management of herd structure to reduce number of cow-days of nonproductive animals. Non-milk producing animals in dairy herds include the replacement heifers and dry cows; this population typically has the same number of animals as the number of milking cows. These animals are significant contributors to the “methane costs” of producing milk at the herd level. The number of replacement animals needed in the herd is a reflection of the reproduction, health, and business goals of the dairy. Reducing age at first calving, reducing heifer mortality and morbidity, and lower whole-herd culling levels will reduce the number of replacement heifers needed and decrease whole-herd methane emissions. It is very reasonable to assume that a 2-month reduction in the national average of age at first calving and a 5% reduction in average culling level could reduce whole-herd methane emissions by more than 5%. Large reductions would lead to greater reductions in whole herd methane emissions and methane per unit of milk. To implement these management strategies, research is needed to enhance the health, nutrition, and growth of heifers as well as improving reproduction, health, and performance of the lactating cows (Area 5).

Area 7. Development and refinement of methane measurement techniques. The existing, validated techniques for measuring methane emissions from animals are very expensive, labor-intensive, and not applicable to measuring methane from large number of animals or animal groups under more typical “field” situations. At least three new techniques are being developed that would overcome these limitations, but they need to be tested against the “gold standard” of respiration calorimetry chambers. Research to improve methane measurement techniques will enhance Areas 2 through 6 above. As such, contributions to improvement in methane emissions per unit of milk by this area are indirect, but could significantly improve both the speed of development as well as the accuracy, precision, and repeatability of the science.

Area 8. Modelling effort to quantitatively integrate the knowledge gained in the above area. Each of the research areas above represents only a part of enteric methane emissions in dairy cattle and dairy farms. To be able to fully utilize the information gained in that research, it must be integrated to provide quantitative evaluations of methane emissions per unit of milk production, per animal, per farm, and possibly per geographical region levels of aggregation. Because of the complexity, time frame, and number of variables involved, computer modelling and assessment is only the method available to assess methane emissions from entire farm systems, regions, or countries. Models are a research tool that will aid in advancing knowledge in ruminant nutrition and a decision-making tool in dairy cattle management. Wherever possible, models should include the economics of dairy profitability and the potential for optimization (minimizing methane emissions while improving profitability). Improved accuracy or reduced variability associated with these predictions should help integrate all research objectives into a common goal to sustainably reduce enteric methane emissions while maintaining or improving milk production and dairy farm profitability. Of particular note is the need to integrate beef and dairy life-cycle assessments to eliminate the double accounting that currently exists in enteric methane emissions. The contribution of modelling to reducing methane emissions per unit of milk is indirect and will be manifested through accomplishments in Areas 1 to 6.

The research areas described above all have significant potential to contribute to that reduction, and many of the areas will complement each other (Figure 2). There are very good scientists at institutions across the U.S. with the capabilities of conducting the needed research, as can be seen in Appendix A. At this time, research funding is a major limitation. In the next two decades, having young, well-trained scientists to replace the current experts will become a challenge. To cultivate research that leads to improved strategies and techniques to reduce methane emissions by the dairy industry, a balance must be struck between supporting research that allows the curiosity of individual scientists and the novelty of their research to flourish, while addressing the biological, physical, and economic complexity of systems which requires teams of scientists with various areas of expertise. This *Cow of the Future* project is designed to foster team development by coordinating communication among scientists and the use of facilities and equipment. These *Research Priorities* have identified major focus areas which should reduce redundancy, improve research efficiency, and increase the overall impact of the research to the dairy industry.

In addition to research funding and graduate student training, future research can be promoted through symposia and conferences. Such meetings enhance the exchange of ideas between researchers and are often the seed of new collaborations. Existing opportunities for such exchanges include: 1) the Discovery Conference series, hosted by the American Dairy Science Association (ADSA); 2) the Joint Annual Meeting of ADSA, the American Society for Animal Science (ASAS), and their affiliates; and 3) the international Greenhouse Gases and Animal Agriculture Conference (GGAAC). A number of opportunities exist for co-operation and collaboration between U.S. scientists and international scientists, including the Global Research Alliance (<http://www.research-alliance.net/index.html>) and LEARN (Livestock Emissions & Abatement Research Network, <http://www.livestockemissions.net/>). Several countries have invested heavily in methane abatement research in livestock through their agricultural research institutions, and private industry is also contributing.

As an additional consideration, many of the research projects proposed in the Expressions of Interest that were submitted to the Innovation Center for U.S. Dairy would benefit the beef industry as well. There is substantial amount of synergy that can be captured with the dairy and beef industries working together.

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Appendices

Appendix A: Expressions of Interest for Future Research

Expressions of Interest (EOIs) describing planned, future research from more than fifty investigators across the U.S. were submitted to The Innovation Center for U.S. Dairy.

Investigator(s)	Institution	Title/topic	Research Area
Dr. Robin Anderson	USDA/ARS Southern Plains College Station, TX	Methane-inhibiting compounds that also serve as alternative electron acceptors	1. Rumen microbial ecology 2. Rumen modifiers
Dr. Lou Armentano Dr. Michel Wattiaux Dr. Kent Weigel Dr. Randy Shaver Mr. Pat Hoffman Dr. Victor Cabrera Dr. Pam Ruegg Dr. Paul Fricke Dr. Milo Wiltbank others	University of Wisconsin, Madison, WI	Multiple projects: improving milk quality and the efficiency and profitability of its production	3. Feeding management 4. Genetic approaches 5. Management approaches 6. Herd structure management 8. Modelling (whole farm)
Dr. Judith Capper Dr. Roger Cady	Washington State University Pullman, WA Elanco Animal Health, Greenfield, IN	Modelling efforts to quantitatively integrate dairy performance, on-farm practices, and methane mitigation strategies	8. Modelling (whole farm)
Dr. Albert DeVries	University of Florida, Gainesville, FL	Novel modeling methods to optimize policies on individual farms	8. Modelling (whole farm)
Dr. Jeffrey Firkins	The Ohio State University Columbus, OH	Identification of novel, effective, and economically sound strategies to mitigate methane emissions	1. Rumen microbial ecology 2. Rumen modifiers

Dr. Alvaro Garcia Dr. Kenneth Kalscheur Dr. Arnold Hippen Dr. David Schingoethe	South Dakota State University, Brookings, SD	Group feeding as a method to reduce greenhouse gas emissions	3. Feeding management
Dr. Mark Hanigan	Virginia Tech University Blacksburg, VA	Improving nutrient requirement models & development of genetic selection tools	3. Feeding management 4. Genetic approaches 8. Modelling (animal performance)
Dr. Alex Hristov	Penn State University State College, PA	Mitigation of enteric and manure GHG emissions from dairy operations	2. Rumen modifiers 8. Modelling (whole farm)
Dr. Ermias Kebreab Dr. Frank Mitloehner Dr. April Leytem Dr. Bill Salas Dr. Mark Lubell	University of California, Davis, CA	Developing a process-based model for estimating methane emissions from dairy operations	8. Modelling (whole farm)
Dr. Joanne Knapp Dr. Normand St-Pierre	Fox Hollow Consulting, LLC Columbus, OH The Ohio State University Columbus, OH	Development of equations and a software tool to predict changes in methane emissions from altering ingredient use in dairy rations	3. Feeding management 8. Modelling (animal performance)
Dr. Richard Kohn Dr. Seon-Woo Kim	University of Maryland College Park, MD	Developing a mathematical model of rumen microbial metabolism	8. Modelling (rumen)
Dr. Neal Martin Dr. Wayne Coblenz Dr. Paul Weimer Dr. Richard Muck others	USDA/ARS Forage Research Center, Madison, WI	Multiple projects	3. Feeding management 6. Herd structure 8. Modelling (rumen)

Dr. John Patterson Dr. Bruce Applegate Dr. Shawn Donkin Dr. Paul Ebner Dr. Susan Eicher	Purdue University West Lafayette, IN	Inhibiting methanogens and trapping hydrogen into acetic acid	1. Rumen ecology 2. Rumen modifiers
Dr. Mark Powell Dr. Glen Broderick Dr. Michel Wattiaux	USDA/ARS Forage Research Center, Madison, WI University of Wisconsin, Madison, WI	Evaluation of long-term strategies to reduce methane emissions, other GHG, and ammonia to improve sustainability	2. Rumen modifiers 3. Feeding management
Dr. Heidi Rosso Dr. Deanne Meyer	University of California Davis, CA	Using mechanistic modeling techniques to reduce GHG emissions	8. Modelling (whole farm)
Dr. Alan Rotz	USDA/ARS University Park, PA	Whole-farm modeling to quantitatively integrate new knowledge for reducing dairy cattle emissions	8. Modelling (whole farm)
Dr. Mike VanAmburgh Dr. Tom Overton Dr. Larry Chase	Cornell University, Ithaca, NY	Continued development of the CNCPS nutrient management model	8. Modelling (animal performance)
Dr. Bill Weiss	The Ohio State University Wooster, OH	Use of residual feed intake to improve feed efficiency of lactating cows	3. Feeding management
Dr. Abraham Woldegebriel Dr. Muluemebet Worku Dr. Aja Moore	North Carolina A&T University, Greensboro, NC	<i>In vitro</i> screening and <i>in vivo</i> evaluation of potential methane-reducing compounds	2. Rumen modifiers
Dr. Zhigou Wu Dr. David Galligan Dr. James	University of Pennsylvania, New Bolton Center, PA	Multiple projects	3. Feeding management 4. Herd structure 8. Modelling (whole farm)

Ferguson Dr. Zhegxia Dou Dr. Essi Evans	Technical Advisory Services, Ontario		
Mr. Wiebe Dykstra Dr. Dewayne Dill Mr. Tom Gray	Atlantic Dairy & Forage Inst., New Brunswick Dalex Livestock Services Bloomington, MN		
Dr. Zhongtang Yu	The Ohio State University, Columbus, OH	Mitigation of methane production from the rumen: an integrated approach	1. Rumen ecology 2. Rumen modifiers

Appendix B: Experts in the Advisory Group

Mr. Matthew Welch, Project Coordinator	The Innovation Center for U.S. Dairy
Dr. Jeffrey Firkins, Chair	The Ohio State University
Dr. Joanne Knapp, Facilitator	Fox Hollow Consulting, LLC
Dr. James Aldrich	Provimi North America
Dr. Roger Cady	Elanco Animal Health
Dr. Alex Hristov	Penn State University
Dr. William Weiss	The Ohio State University
Dr. André Wright	University of Vermont

Mr. Matthew Welch is the Manager, Sustainable Business Development for Dairy Research Institute. In his role, Matthew focuses on strategy, stakeholder engagement, and securing support for the U.S. Dairy Sustainability Commitment, an industry-wide effort that is currently working to reduce greenhouse gas emissions of fluid milk by 25% by 2020. Matthew has more than 12 years of experience in general management, sustainable development and consulting. In that time, he has run a profitable retail food business; assisted small-scale agribusinesses in Peru with the U.S. Peace Corps; conducted revenue generation projects for nonprofit organizations; and consulted Fortune 500 companies including PepsiCo and Ecolab Inc. Matthew holds a bachelor's degree in international studies from DePaul University, a master's degree in natural resources and environment from the University of Michigan, and an MBA from the Ross School of Business. He is co-author of *Hybrid Organizations: New Business Models for Environmental Advisory*.

Dr. Jeffrey Firkins is a Professor in Animal Sciences at The Ohio State University (OSU). A native of Illinois, he attended the University of Illinois where he received his B.S. in Animal Science and M.S. and Ph.D. in Ruminant Nutrition. He joined the faculty at OSU in 1987 and was promoted to Professor in 2000. Jeff teaches courses in ruminant nutrition, advanced ruminant nutrition, and carbohydrate and lipid metabolism to undergraduate and graduate students. He is the Director of the OSUN interdisciplinary doctoral program in nutrition. Jeff has served as Section Editor for the Journal of Animal Science and is currently serving as an editor for the British Journal of Nutrition and on the planning committees for the International Symposium on Ruminant Physiology and the Conference on Gastrointestinal Function. Jeff's research program has focused on digestibility of feed ingredients, rumen function with a strong emphasis on the role of rumen protozoa, and quantitative determinations of nutrient utilization. He has written more than 100 abstracts, 90 refereed articles and book chapters, and 60 conference proceedings. In recognition of his accomplishments, Jeff has received the OARDC

Junior Faculty Award (1999), the ADSA Applied Dairy Nutrition Award (2003), and the Gamma Sigma Delta Research Award of Merit (2006).

Dr. Joanne Knapp is the President of Fox Hollow Consulting, LLC. She grew up in western Pennsylvania and attended Cornell University, graduating with a B.S. with Honors in Animal Science. She earned her M.S. and Ph.D. degrees in Nutrition at the University of California-Davis under the direction of Dr. Lee Baldwin. She spent another year at UC Davis as a post-doctoral researcher, modelling methane emissions from ruminants, before moving on to Ohio University for post-doctoral research in molecular and cellular biology. In 1997, she joined the faculty in Animal Science at the University of Vermont where she was active in teaching, research, and outreach. In 2004, she made a career leap into industry, returning to California to become Director of Nutrition for the San Joaquin Valley operation of J.D. Heiskell & Co. In 2007, she started her own consulting business, providing technical expertise to the food, feed, and pharmaceutical industries, which is now based in Columbus, OH. She has authored 20 peer-reviewed papers, 37 abstracts, and 10 lay articles and conference proceedings. To date, she has mentored more than 27 undergraduate and 6 graduate students. She has served on the *Journal of Dairy Science* editorial board and the Joint Annual Meeting lactation biology and ruminant nutrition planning committees. Currently, she is involved with the organizing committee for the Midwest ARPAS chapter, holds an adjunct appointment in Animal Sciences at The Ohio State University, and provides *ad hoc* review for several scientific journals.

Dr. James Aldrich is a native of New York. He received his B.S. and M.S. from Cornell University and Ph.D. from The Pennsylvania State University. He served as a Dairy Extension Specialist for Cornell Cooperative Extension for 9 years in Eastern NY. Jim is currently Director of Ruminant Nutrition for Provimi North America, Inc. located in Lewisburg, OH where he has been since 1991. In his current role, Jim oversees a current staff of 17 ruminant nutritionists and dairy specialists providing technical services to feed companies, consultants, and producers in the US, Canada and Japan through the brands Akey and Vigortone Ag Products. Jim is member of the global Provimi Feed Solutions organization. Within this organization Jim collaborates with colleagues in other areas of the world to advance ruminant nutrition, including initiatives to reduce the carbon footprint of animal agriculture. Dr. Aldrich is a member of the American Dairy Science Association and the American Registry of Professional Animal Scientists (ARPAS) where he previously served on the Board of Directors as treasurer.

Dr. Roger Cady is a native of New York and received his B.S., M.S. and Ph.D. in Animal Breeding from Cornell University. Dr. Cady has been employed in several technical roles during his 10 year employment at Monsanto and Elanco Animal Health. He currently serves as a Sr. Technical Advisor for Elanco Animal Health. In this role, Dr. Cady works with the dairy industry and retail chain providing sound science to support sustainable agricultural practices. Throughout his career, Roger has worked to integrate research information with practical on-farm management. He is currently focused on methods to reduce natural resource use in the production of food animal protein and promote environmentally sustainable practices in the food animal industry. Prior to working in industry, Roger served as professor and extension dairy specialist for 18 years at the University of New Hampshire and Washington State University. While working in the academic sector, he co-founded and served as moderator of *Dairy-L*, a

popular international e-mail based discussion group covering issues important to dairy herd and dairy cattle management. He is a founder of the Dairy Calf and Heifer Association (now PDHGA). Recognition Roger has received during his career include the *Alfa-Laval Agri, ADSA Award* for excellence in dairy cattle extension, and in 1999 PDHGA honored him with an award named in his honor, *The Cady Award*, for excellence in service to dairy heifer growers. Dr. Cady is a member and past officer in the American Dairy Science Association (ADSA) and has served on various national and state industry committees and boards.

Dr. Alex Hristov is Associate Professor of Dairy Nutrition with the Department of Dairy and Animal Science, Pennsylvania State University. He has a Ph.D. in Animal Nutrition from the Bulgarian Academy of Agricultural Sciences. His career started at the Institute of Animal Sciences in Kostinbrod, Bulgaria. Dr. Hristov has worked at the USDA-ARS Dairy Forage Research Center in Madison, WI and the Ag Canada Research Center in Lethbridge, AB. He was Assistant and Associate Professor of Dairy Nutrition with the Department of Animal and Veterinary Science at the University of Idaho, Moscow, ID. He joined Pennsylvania State University in 2008. He teaches Feeds and Diet Formulation, the nutrition portion of Advanced Dairy Management, and a graduate level class, Ruminology. Dr. Hristov's main field of research is dairy cow nutrition, specifically improving the efficiency of utilization of dietary nutrients for milk synthesis and reducing nutrient losses and gaseous emissions from dairy operations. Dr. Hristov has been actively presenting his research at various scientific and extension forums and has published more than 60 refereed-journal articles and book chapters and edited a book (Nitrogen and Phosphorus Nutrition of Cattle; CABI) in the last 10 yrs. He is currently the Division Editor for the Ruminant Nutrition Section, Journal of Animal Science and Associate Editor for the Canadian Journal of Animal Science.

Dr. Bill Weiss, is a Professor of Dairy Cattle Nutrition and Extension Specialist in the Department of Animal Sciences, The Ohio State University. He obtained his B.S. from Purdue University and Ph.D. from The Ohio State University (OSU). He has been on the faculty of OSU since 1989 and was promoted to professor in 1998, and has authored or co-authored 96 peer-reviewed papers, 8 book chapters, 1 book, and 207 papers for conference proceedings. He was a committee member and large contributor to the National Research Council's 7th edition on Nutrient Requirements for Dairy Cattle. To support his research, he has obtained over 3 million dollars in extramural funding. Dr. Weiss' main research areas are: 1) Factors affecting nutrient excretion (especially N) by dairy cows; 2) Factors affecting digestible energy concentrations in diets of dairy cows; 3) Relationships between minerals/vitamins and health of dairy cows (especially mastitis); 4) Effect of variability in supply of nutrients on productivity of dairy cows and profitability of dairy farms. He conducts extension workshops on dairy cattle nutrition and management and teaches an advanced bioenergetics course. Dr. Weiss' contributions to research and extension have been recognized through the receipt of the Distinguished OARDC Junior Scientist Award (1997), American Feed Industry Association Dairy Nutrition Research Award (2000), Gamma Sigma Delta Award of Merit for Extension (2005), and the Pioneer Hybrid Forage Award (2006).

Dr. André Wright is an Associate Professor and Chair of the Department of Animal Science at the University of Vermont, with joint appointments with the Department of Medicine, and the

Department of Microbiology and Molecular Genetics. He also holds appointments as an Adjunct Associate Professor in the School of Chemistry and Molecular Bioscience at the University of Queensland (Australia), and as an Associate Graduate Faculty member at the University of Guelph (Canada). Before coming to Vermont, André was a Research Group Leader at the Australian Government's Commonwealth Scientific and Industrial Research Organization (CSIRO) in Brisbane. Dr. Wright's internationally recognized research uses cutting-edge molecular techniques to examine the microbiome of the animal and human gut to better understand the interactions between host genetics, immune responses, and the gut microbiota. Dr. Wright received his PhD in 1998 from the University of Guelph and has published 45 peer-reviewed papers and 7 invited book chapters. He serves on the Editorial Boards for 4 journals, and has served as an ad hoc reviewer for the NSF, USDA and NIH. In 2008, a ciliated protozoan was named after him, *Apokeronopsis wrighti* in recognition of his contributions to microbiology.