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Invited review: Learning from the future—A vision for dairy farms and cows in 2067

J. H. Britt,*[1] R. A. Cushman,† C. D. Dechow,‡ H. Dobson,§ P. Humblot,# M. F. Hutjens,‖ G. A. Jones,¶ P. S. Ruegg, I. M. Sheldon,†† and J. S. Stevenson‡‡**
*Department of Animal Science, North Carolina State University, Raleigh 27695-7621
†USDA Agricultural Research Service, US Meat Animal Research Center, Clay Center, NE 68933
‡Department of Animal Science, Pennsylvania State University, University Park 16802
§School of Veterinary Science, University of Liverpool, Neston, United Kingdom CH64 7TE
#Department of Clinical Sciences, Swedish University of Agricultural Sciences, Uppsala, 750 07, Sweden
‖Department of Animal Sciences, University of Illinois, Urbana 61801
¶Central Sands Dairy, De Pere, WI 54115-9603
**Department of Animal Science, Michigan State University, East Lansing 48824-1225
††Swansea University Medical School, Swansea, Wales, United Kingdom SA2 8PP
‡‡Department of Animal Sciences and Industry, Kansas State University, Manhattan 66506-0201

ABSTRACT

The world's population will reach 10.4 billion in 2067 with 81% residing in Africa or Asia. Arable land available for food production will decrease to 0.15 ha per person. Temperature will increase in tropical and temperate zones, especially in the Northern Hemisphere, and this will push growing seasons and dairy farming away from arid areas and into more northern latitudes. Dairy consumption will increase because it provides essential nutrients more efficiently than many other agricultural systems. Dairy farming will become modernized in developing countries and milk production per cow will increase, doubling in countries with advanced dairying systems. Profitability of dairy farms will be the key to their sustainability. Genetic improvements will include emphasis on the coding genome and associated noncoding epigenome of cattle, and on microbiomes of dairy cattle and farmsteads. Farm sizes will increase and there will be greater lateral integration of housing and management of dairy cattle of different ages and production stages. Integrated sensors, robotics, and automation will replace much of the manual labor on farms. Managing the epigenome and microbiome will become part of routine herd management. Innovations in dairy facilities will improve the health of cows and permit expression of natural behaviors. Herds will be viewed as superorganisms, and studies of herds as observational units will lead to improvements in productivity, health, and well-being of dairy cattle, and improve the agroecology and sustainability of dairy farms. Dairy farmers in 2067 will meet the world's needs for essential nutrients by adopting technologies and practices that provide improved cow health and longevity, profitable dairy farms, and sustainable agriculture.

Key words: dairy, future, technology, management

INTRODUCTION

Demand for dairy products and technologies will grow during the next 50 yr for 2 reasons. First, increased per capita income worldwide will boost demand for dairy and other food products from animals, and these products increasingly will provide essential nutrients in developing countries. The Food and Agriculture Organization (**FAO**) of the United Nations states: "Even small amounts of animal source foods can improve the nutritional status of low-income households. Meat, milk and eggs provide proteins with a wide range of amino acids as well as micronutrients such as iron, zinc, vitamin A, vitamin B_{12}, and calcium, in which many malnourished people are deficient" (Kourous, 2011). Second, dairy products efficiently meet nutritional requirements of humans from the standpoint of farming practices. Production of milk uses less land to produce 1 g of readily edible protein than production of other livestock or poultry products and some plant products (Figure 1; Clark and Tillman, 2017; Roser and Ritchie, 2017). Dairy-based diets are superior to vegan-, egg- and omnivore-based diets for maximizing capacity of croplands to feed the greatest number of people while adhering to recommended agronomic practices for various classes of lands (Peters et al., 2016). The advantage of dairy- and egg-based diets over vegan-based diets is

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[1] Corresponding author: jackhbritt@gmail.com

Climate Change

Changes in climate during the next 50 yr will affect where dairy farms and cattle are located and focus more attention on types of cattle that are adaptable to various regions. Climate in the Northern Hemisphere is particularly important because 81% of the world's population lives north of the equator (Lutz, 2012). Similarly, 86% of world's milk from dairy cattle is produced north of the equator (FAOSTAT, 2017).

Global temperature has increased steadily for several decades (Figure 3). This trend has been particularly consistent during the last 5 decades and most forecasts expect it to continue. Forecasts for changes in climate in the Northern Hemisphere include warmer temperatures year-round, greater variation in precipitation, and longer growing seasons toward the polar latitudes. This forecast is also true for the Southern Hemisphere but it is dampened by tempering effects of the oceans. It is predicted that the future climate will have longer periods of both drought and excess rainfall, with more severe weather incidents.

The warming climate could add arable land to produce food and feed crops in northern regions of North America, Europe, and Asia; however, some of this could be offset by losses of arable land associated with less rainfall and less water for irrigation of crops in other areas of each region. Changes in climate will cause shifts in locations of dairy cows and farms. For example, in the United States, approximately 42% of milk produced currently originates in states that are expected to have severe water shortages by 2067 (Figure 4). A significant portion of dairy cows in these areas will be relocated to areas with more sustainable water supplies and adequate growing seasons. Areas in North America that are most suitable for dairy expansion are in the Upper Midwest and Great Lakes regions and the central provinces of Canada. These areas are forecast to have adequate water resources and longer growing seasons in 2067. Similarly, Russia will have more land suitable for crop production in its northern latitudes and dairy cows will move into these areas.

DAIRY CONSUMPTION AND PRODUCTION

Worldwide, annual consumption of dairy products (fresh milk equivalent basis) currently averages about 87 kg per person and is expected to increase to 119 kg per person worldwide by 2067, based on extrapola-

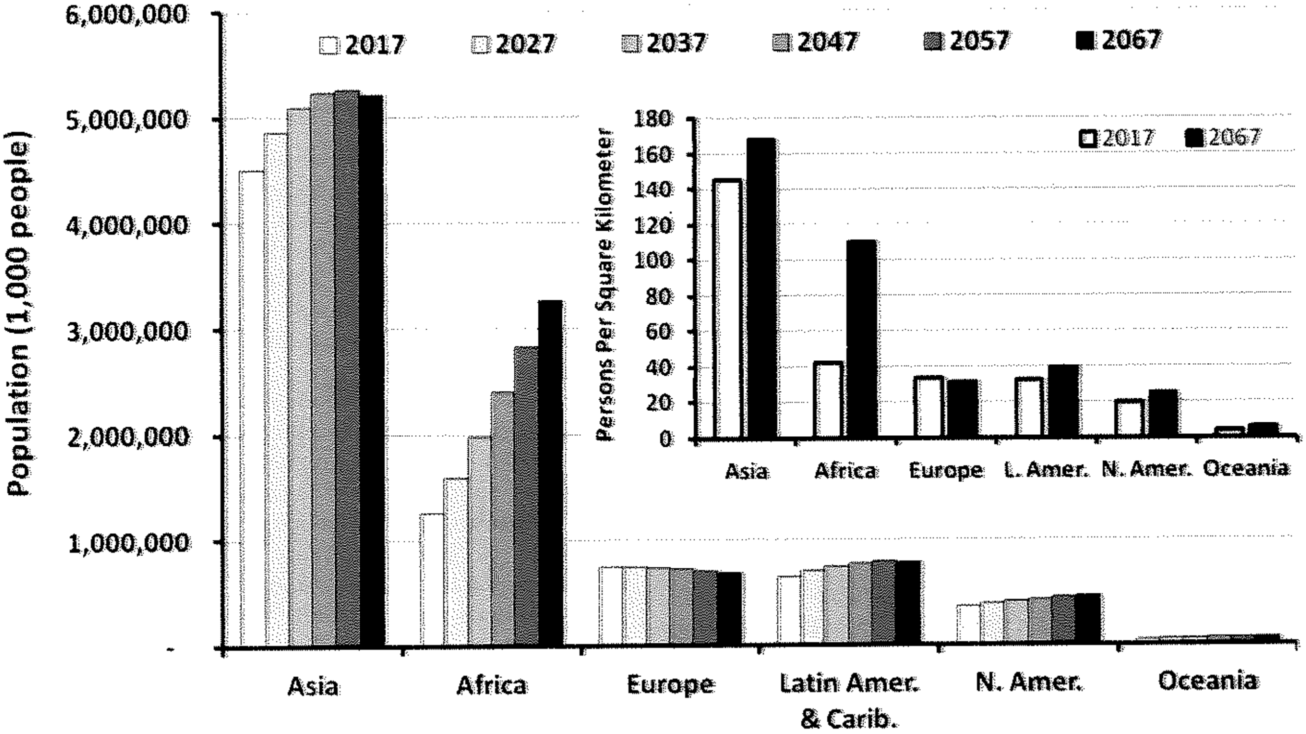

Figure 2. Estimated population of world's regions from 2017 to 2067 and estimated population density for 2017 and 2067. Raw population data downloaded from United Nations (2017). Inset shows population density (persons per km^2) for each region. L. Amer. = Latin America; N. Amer. = North America; Carib. = Caribbean.

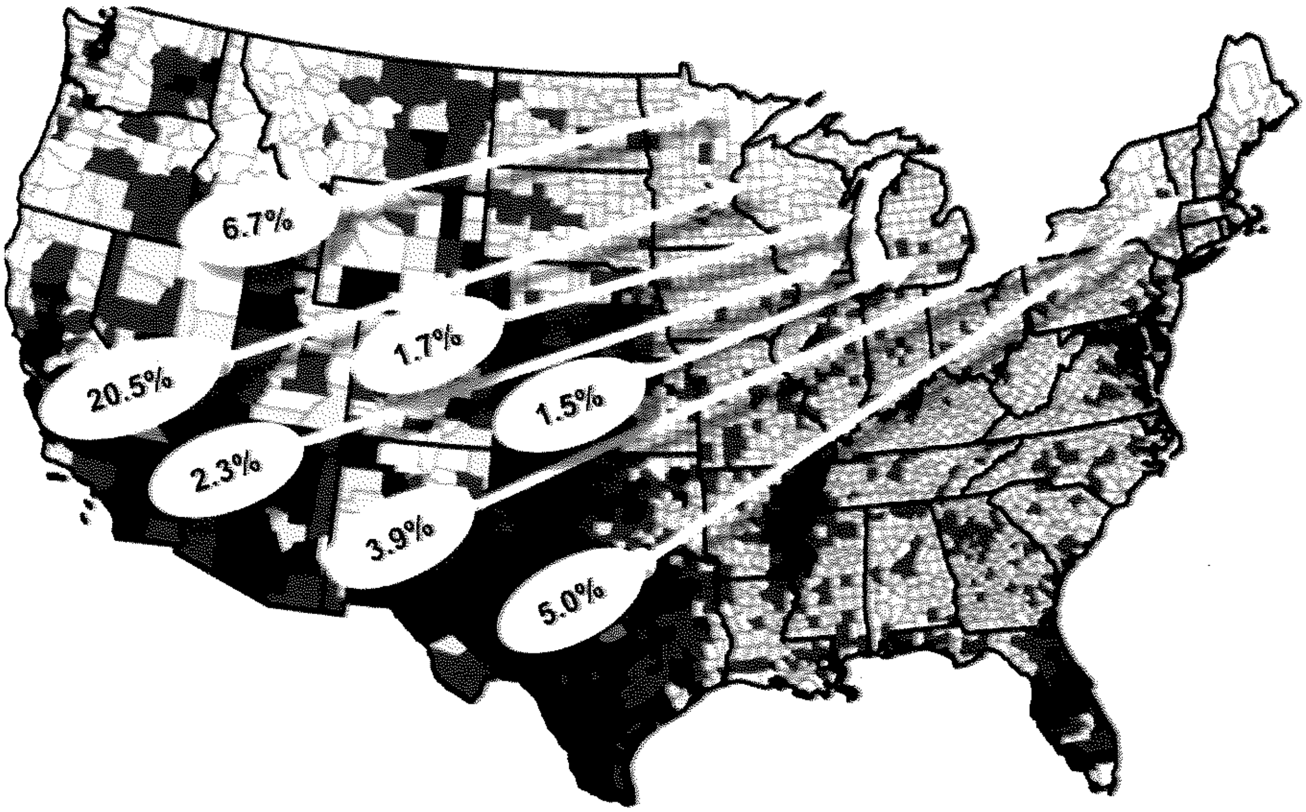

Figure 4. Projected relocation of dairy farming from US regions with shortages of water to North American regions with adequate water during the next 50 yr. Darker shaded areas will have less sustainable water supplies with current projections of climate change. Percentage in the base of each arrow represents estimated percentage of US milk produced currently in that state. Original underlying map converted to black and white and used with permission (Roy et al., 2012).

was privatized and began with 3 types of production: (1) milk produced for the family or household; (2) milk produced by smallholders for sale locally to individuals, local spot markets, or collection centers (emerging producers); and (3) milk produced for sale directly to commercial processing enterprises (industrialized farms). This latter group included herds with about 50 cows or more. Types of cropping and feeding systems overlapped among these 3 dairy farm settings in Zambia. Grazing was a primary source of feed but even household units purchased fodder and grains to feed cows year-round or during certain seasons.

Common obstacles hindered transition among stages (household, smallholder, and industrial). To move from household to smallholder required improved sanitation, utilization of stainless-steel milk pails, and compliance with minor milk quality standards. Investments in equipment in this transition were modest, but requirements for adhering to sanitation and quality standards challenged traditional households and smallholders. The greatest challenge to moving into the industrial category was the cost of equipment and facilities to sell directly to milk processors. This required milking facilities with concrete floors and on-farm refrigeration of the milk. Sanitation standards were also increased so the milk would meet grade-A standards. Moving to the industrial level required access to more land for grazing and feed production. Many producers dropped out at the smallholder stage and some dropped out after reaching the industrial stage.

Milk processing plants in Zambia paid higher prices to dairy producers in their country than prices paid at the same time in North America and Europe, and it was more profitable for processing plants to import milk powder from international suppliers than to produce products within the country. Nevertheless, the dairy industry in Zambia continues to grow in part because of a focus on food security. This recent experience in Zambia reflects historical maturation of the dairy industry in developed countries.

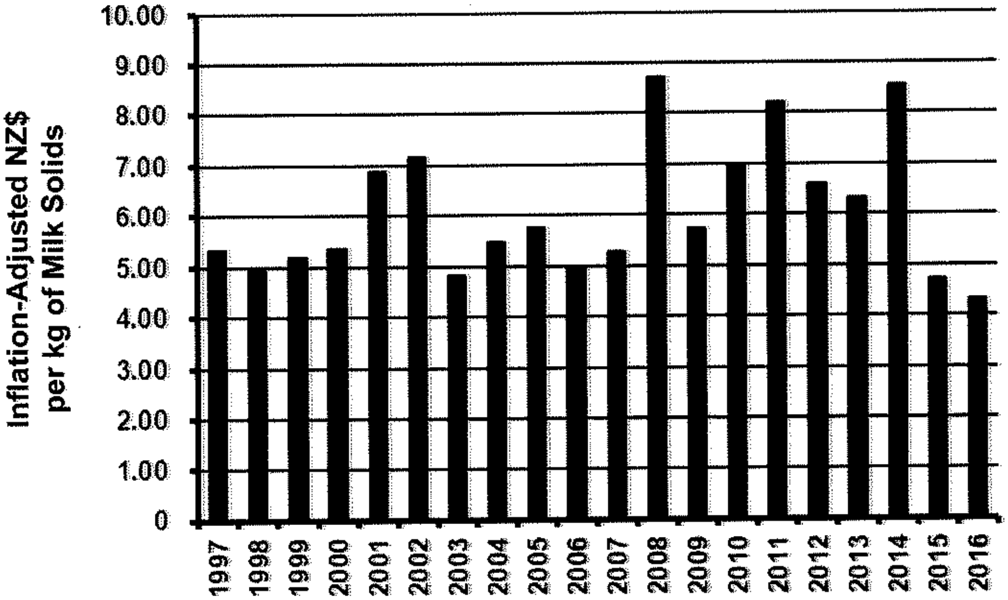

Figure 6. Volatility in inflation-adjusted prices paid to dairy farmers in New Zealand during the last 20 yr. Over this 20-yr span, NZ$1 was equivalent to $0.62. Adapted from NZ Dairy Statistics 2015–2016 (Dairy NZ, 2016).

yr (Figure 6). During this period, the amount paid (inflation-adjusted NZ$/kg of milk solids) ranged from NZ$4.30 to NZ$8.72 (over this 20-yr span, NZ$1 was equivalent to $0.62). This volatility in prices paid to farmers for milk inevitably drives less profitable farms out of business. Practices such as supply management limit the effect of lower prices in some countries, but global trade agreements are gradually dampening such practices.

Challenges for Exporters

Today's major dairy exporting countries are in Europe, North America, and Oceania (Figure 7). Asian and African countries export small percentages of production (inset, Figure 7). Globally, milk processing is dominated by multinational companies, with 10 being headquartered in Europe, 6 in North America, 2 in China, and 1 each in Japan and New Zealand (Rabobank, 2017). Thus, 16 of the top 20 dairy processing companies are headquartered in major exporting regions. These processing companies have facilities scattered across the globe and control much of the tradable dairy products in global commerce.

These exporting regions and associated companies are positioned to meet a significant portion of growth in future demand for dairy products, primarily because they have capacities to produce more milk and to process it into exportable products, and their domestic populations are growing slowly or declining. These regions also have the lowest GHG output per unit of milk leaving the farm gate (Opio et al., 2013). The GHG outputs (kg of CO_2 equivalents/kg of fat- and protein-corrected milk) range from about 1.3 for North America, Eastern and Western Europe, Russia, and Oceania to 7.4 for sub-Saharan Africa. Among 10 countries with the greatest number of dairy cows today, 6 are in regions with the greatest GHG output per unit of milk (Figure 5).

A challenge for dairy exporting countries and regions will be to develop products that provide affordable dairy-based nutrients to meet the needs of children and adults in countries in which demand will exceed local or regional supply. Meeting this need will require a different strategy than is common practice, where components not consumed within domestic and regional markets are exported. For example, in 2016, the United States exported about 4% of its milk equivalents expressed on a milk-fat basis, and about 17% expressed on a skim-milk basis, illustrating that domestic supply of milk fat was close to domestic demand, whereas other components such as lactose were in oversupply. In the future, importing countries will seek products that are designed for their specific tastes and customs, so there will be a shift away from shipping surpluses to shipping value-added products for consumers in targeted nations.

It will be necessary to assess current and projected population pyramids in countries to develop age-specific products for export. For example, projections show

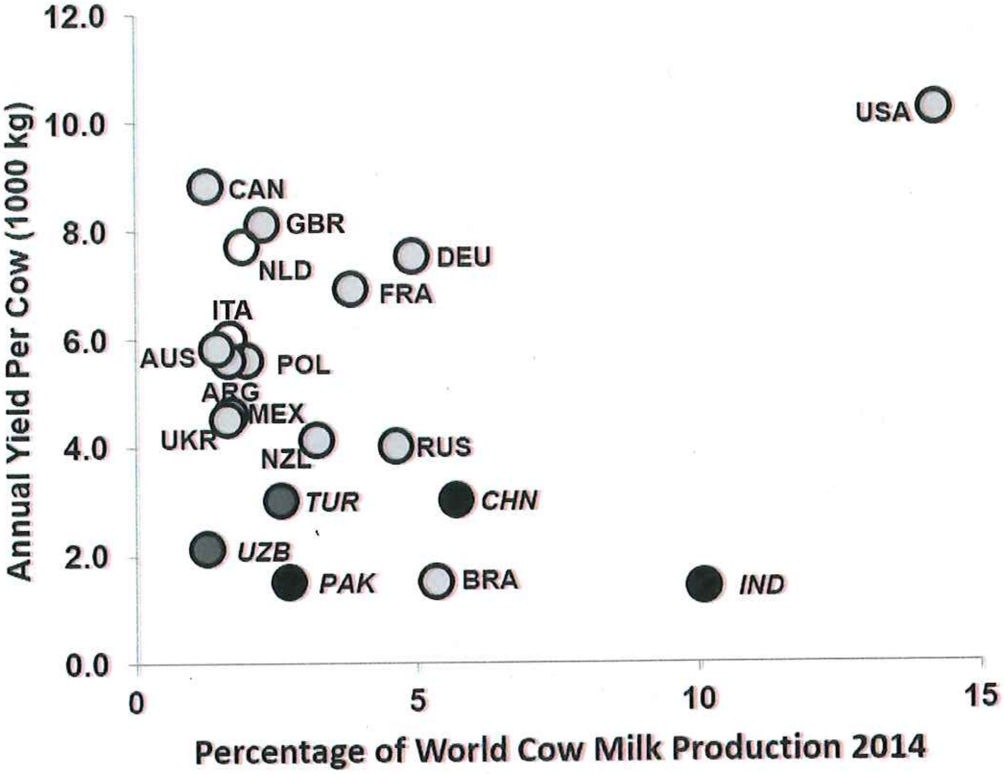

Figure 8. Annual yield of milk per cow and percentage of world's cow milk produced by the top 20 producing countries in 2014. These countries produced 74.4% of world's cow milk. Closed (black or dark gray) circles represent countries in Africa or Asia. Circles with either light gray or dark gray shading in their centers are countries that we predict will have the greatest opportunity to export dairy products in 2067. ARG = Argentina, AUS = Australia, BRA = Brazil, CAN = Canada, CHN = China, DEU = Germany, FRA = France, IND = India, ITA = Italy, MEX = Mexico, NLD = the Netherlands, NZL = New Zealand, PAK = Pakistan, POL = Poland, RUS = Russia, TUR = Turkey, GBR = Great Britain, UKR = Ukraine, USA = United States, UZB = Uzbekistan (country codes are from http://www.fao.org/countryprofiles/iso3list/en/).

lize sensors and technologies to improve sustainability, particularly associated with soil and crop health, water quality, and emissions. Lateral and vertical integration in the dairy farming sector will lead to more specialization in managing cattle of different ages and stages of production. The number of dairy farms will decline and herd sizes will increase; however, the total number of dairy cows will drop as production per cow climbs in developing countries.

Milk Production of Dairy Cows in the Future

We project that milk volume and solids produced per cow will climb at an accelerated rate, driven by genomic selection and improvements in quality and digestibility of feedstuffs.

We project that annual milk or milk solids yields for dairy cows in the United States and New Zealand (**NZ**) will double by 2067 (Figure 9). For these projections, we fit linear and exponential curves to historical US milk yield and NZ milk solids yield data. Within country, linear and exponential fits were essentially identical (US: linear $R^2 = 0.9896$ and exponential $R^2 = 0.9868$; NZ: linear $R^2 = 0.8484$ and exponential $R^2 = 0.8415$). We discussed the trend lines and opined that average annual milk solids yield would double in 50 yr, reaching about midway between linear and exponential extrapolations. A rate higher than the linear extrapolation is justified on the basis that genomic selection has accelerated the rate of genetic progress more recently. Milk volume will continue to rise due to its correlated response to higher solids yield, but it is less likely to double because most market signals will continue to favor milk solids over milk yield.

Dairy production systems in the United States and New Zealand differ in breed composition and how cows are fed and managed. Dairy farms in the United States are smaller than those in New Zealand and typically depend more on stored feed, including concentrates from grains and oilseeds. Dairy farms in New Zealand typically depend on intensive grazing for feed, with less reliance on stored feeds. The formulas for payments to identified, these genes will be moved within and among breeds by gene editing. Otherwise, genetic and epigenetic markers for such traits will be included in genomic selection indices. Trans-genes or synthetic genes may be added by inserting sequences into existing genomes.

Genetic Changes in Dairy Cattle

Impact of Genomic Selection. Generation interval for dairy cattle will continue to decline through combined use of genomic selection, in vitro fertilization (IVF), and other advanced reproductive technologies (Humblot et al., 2010; Pryce et al., 2012; Weller et al., 2017; Cole and VanRaden, 2018). After the first genomic summary was published for US Holstein cattle in 2009, the rate of genetic progress for several traits in Holsteins accelerated (García-Ruiz et al., 2016). Rate of genetic progress per year for yield traits increased by about 50%, but progress increased 3- to 4-fold per year for health and longevity traits. In the future, more phenotypes will be added to the list of traits that will be estimated by genomic evaluations, thus accelerating genetic progress to improve animal health and welfare, feed efficiency and excretion of pollutants such as methane. In the past, it has been challenging to incorporate such phenotypes into classical quantitative selection schemes, but with genomic markers for these traits, it is becoming simpler (Boichard et al., 2015; Cole and VanRaden, 2018).

Genetic progress also will benefit from the reduction in generation interval associated with genomic testing and use of reproductive technologies. Since 2009, the generation interval for bulls entering AI in the United States has dropped from approximately 7 to 2.5 yr (García-Ruiz et al., 2016). This interval is approaching the theoretical limit for nonsurgical approaches in which oocytes can be retrieved and sperm recovered at about 8 mo of age in well-fed dairy heifers and bulls (Byrne et al., 2017), producing a generation interval of 17 mo. Generation interval could be dramatically less by 2067 through reproductive innovation. Production of viable oocytes from embryonic stem cells has been demonstrated in mice (Hayashi et al., 2017). This could allow genomically tested embryos to be used as parents and reduce the generation interval to <1 yr, but such techniques have not yet been developed for cattle.

During the next 50 yr, use of genomic selection will spread rapidly among breeds that are underrepresented in current world dairy genomic databases (Boichard et al., 2015). Genomic predictions for these breeds are not used currently because of limited data and poor reliability across breeds. Our ability to estimate SNP associations from mixed and crossbred populations will improve and allow a small amount of phenotypic data from an underrepresented breed to be supplemented by large phenotypic databases from major breeds to build more robust databases for breeds worldwide (Hozé et al., 2014).

Genetic Improvement of Health, Welfare, Feed Efficiency, and Methane Excretion. Selection for health- and environmental-related traits will expand as new genomic selection indices are added (Cole and VanRaden, 2018). Existing bovine genes or alleles that benefit cattle exposed to rising temperatures may be moved among breeds by gene editing. For example, a Holstein line that was developed through conventional breeding has a gene for heat tolerance (*SLICK* gene), and cows in this line show better tolerance to heat stress (Dikmen et al., 2014). Gene editing could be used to quickly move this *SLICK* gene into other lines or breeds.

Genomic selection will expand in areas related to immunity, disease resistance, reproduction, and mastitis (Thompson-Crispi et al., 2012; Miglior et al., 2014; Parker Gaddis et al., 2014). Holsteins with greater immunity identified by a patented genomic test that measures cell- and antibody-mediated immune responses show stronger immunity and have longer herd life and better reproductive performance (Thompson-Crispi et al., 2012). Genetic markers for antibody- and cell-mediated immune responses have been identified in Holstein cows and bulls, and semen is available for sires that have these greater immune responses (Thompson-Crispi et al., 2014).

Metabolic stress in transition cows is associated with loss of BW and increased metabolic diseases, lameness, and infertility; however, 2 recent studies provide evidence that we can select cows that are more metabolically robust during early lactation. Zachut and Moallem (2017) found that relative postpartum BW loss in Holstein cows differed and was repeatable during the first 5 lactations. Cows that exhibited less BW loss produced the same amount of milk during lactation as those that lost more BW, but those with lower BW loss had better fertility. Ha et al. (2017) identified a genetic component to estimate metabolic change during early lactation in Brown Swiss cows. Brown Swiss bulls differed in types of daughters that they sired, and daughters that were more metabolically robust had extended functional lifetimes in herds. As genetic markers for these traits are identified, there will be increased emphasis on selecting cows that are affected less by metabolic changes during the postpartum period.

Selection for residual feed intake, which estimates efficiency of utilization of feed by individual animals, improves efficiency of milk and meat production and simultaneously lowers methane produced per unit of milk or meat (Manzanilla-Pech et al., 2016; VanderHaar et

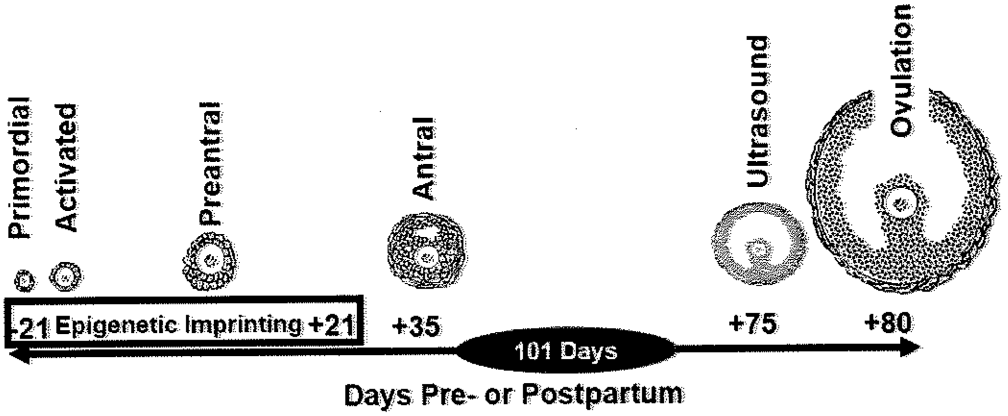

Figure 10. Example of an epigenetic-type effect on the developing bovine oocyte that is subjected to changes in energy balance and other adverse environmental conditions during the transition period in dairy cows. The oocyte is activated about 21 d prepartum and ovulated about 80 d postpartum. It is affected by adverse metabolic or disease conditions during the transition period that subsequently affect its survival after fertilization. Model developed based on Britt (1992) and Carvalho et al. (2014).

cows reduces the number of antral follicles in heifers born to those restricted dams (Mossa et al., 2013). Reducing rate of gain during a few weeks before expected puberty increases the number of primordial follicles near first breeding (Freetly et al., 2014; Amundson et al., 2015). Inflammation associated with disease reduces the number of primordial follicles (Bromfield and Sheldon, 2013). Such latent effects will become important targets for management during the next 50 yr.

Genomics in the future will expand to cover these and other traits and will include some RNA sequencing and DNA methylation profiling as part of an animal's genomic evaluation. Connecting the dots on some of these pathways and relationships will make it more feasible to incorporate the epigenome into genomic selection.

Genomes of the Microbiota

Advances in DNA and RNA sequencing technologies are leading to rapid advances in identifying and understanding microbiomes (genomes) of organisms in cattle fed and managed under various conditions (Deusch et al., 2014). Fecal microbiomes of beef cattle differ among cattle receiving different rations within a location, among specific locations within a region, and among different regions of the United States (Shanks et al., 2011).

Although rumen microbiomes are more alike within locations, differences in populations of rumen microorganisms among cows consuming the same TMR in a herd may cause cows to produce milk that differs in composition. Jami et al. (2014) fed primiparous Holstein cows the same TMR during first lactation but found that the ratio of the 2 dominant phyla of rumen organisms (*Firmicutes* and *Bacteroidetes*) ranged from 2:1 to 1:3, and this ratio was correlated ($R^2 = 0.52$) with milk fat yield. Thus, many questions remain about causes of differences in the gastrointestinal microbiome in cattle and how this affects performance and health.

Uncertainty exists about when the gastrointestinal microbiome is established, but substantial evidence indicates that it begins to be established by 2 d after birth (Yáñez-Ruiz et al., 2015). Studies with identical human twins found that genetics plays an important role ($h^2 = 0.39$) in twins having common gastrointestinal organisms (van Opstal and Bordenstein, 2015). It may be possible to use genomic selection to manipulate gastrointestinal microbiomes to improve feed utilization and health of dairy cattle.

Microbiomes of mammary (Oikonomou et al., 2014) and urogenital (Santos and Bicalho, 2012) systems differ among healthy and diseased states in dairy cows, but it is unclear exactly how changes in the microbiome are related to a disease state. As we develop systems for routinely monitoring microbiomes in cattle, manipulating the microbiome may become a key aspect of herd management.

Biological Limits

Scientists, farmers, and consumers often ask whether we are reaching the biological limit in milk production. To address this question, our group examined data from top-yielding cows in the United States. Top individual cow records produced during the last decade were 10 to 14 standard deviation (SD) units greater than the average yield per cow in 2014, indicating that the potential for increased yield is substantial. Similarly, we looked mon design and construction. Management protocols and equipment will be standardized among locations within laterally integrated operations. This standardization will permit lactating cows to move easily from one unit to another during different lactations.

Smaller dairy farm enterprises will collaborate and adopt practices of larger enterprises to remain economically competitive. This will eventually lead to vertical integration of smaller units in commercial dairy sectors. Nevertheless, some dairy farms will remain smaller and independent, with targeted niche markets emphasizing grass only milk or local production. Other small farms may produce milk with proprietary therapeutic products.

Dairy beef will increase in importance because its production generates about one-third of the GHG equivalents per unit weight of product compared with traditional beef production (Opio et al., 2013). Cows with lower genomic ranks in herds will be inseminated with sex-selected sperm from beef sires or will receive terminal-cross embryos from beef-breed donors. This will increase the proportion of dairy farm income generated by sale of animals, and these animals may enter a premium consumer market focused on climate-friendly beef products.

Automation and Robotics

Farms of the future will utilize on-farm and remote sensors, robotics, and automation to improve management of herds, comply with regulations, and reduce the farm's environmental footprint. Data from sensors, robots, and automated equipment will be converted through artificial intelligence to actionable outputs that will inform managers.

Artificial intelligence and machine learning are being used to improve the prediction of complex events such as time of parturition (Borchers et al., 2017). Rapid advances will occur in this area as feedback from sensors, robots, and automated systems is integrated through software that learns and improves prediction or diagnostic accuracy. Sensors monitoring fields where crops are grown and sensors from silos and other feed storage facilities will provide information about digestibility and quality of feed and how this is influenced by field-specific and storage conditions. Added to this sensor information will be data from individual cow intake monitored by 3-dimensional imaging systems. Implantable, biodegradable sensors will monitor mammary gland, liver, and other organs. In-line detectors from each teat cup will monitor teat and udder health, metabolic traits, milk composition, and key hormones. Automated systems will also measure cow BW, body condition, and changes in gait to predict lameness as cows move to and from robots for milking. Milk somatic cell DNA will be monitored to characterize changes in immune and disease status that are reflected in perturbations in key DNA sequences throughout the genome.

Automation and robotics will reduce manual labor on farms. In most developed countries, cows will be milked by robotic systems, and feed will be loaded, mixed, and delivered by driverless vehicles. Energy, soil and crop nutrients, and clean water will be recovered from manure and wastewater on farms through use of anaerobic digesters and specialized osmotic filtration systems. Automation will lead to continued growth in size of dairy farms, because economies of scale will be needed to pay for automated systems. To reduce transportation costs, milk solids will be concentrated on farms, and residual liquid portions containing lactose and some minerals will be re-used in rations. Alternatively, milk with different compositions will be sorted from the cow into tank trucks destined for different milk processing facilities.

Managing "Omics" on the Dairy Farm

There will be increased focus on practices that benefit animals, crops, soils, and farmsteads by managing microbial populations in a farm's microenvironments and through monitoring and managing epigenetic-mediated effects on animals and crops

Managing the microbiome will depend on a clearer understanding of how it is established and maintained in healthy animals. Knowledge of how feed sources and geographic locations affect microbiomes of dairy cattle will expand quickly and lead to manipulation of the microbiomes in various ways and at different stages of life to improve health, welfare, and productivity.

If current concepts are confirmed, that microbiomes of gastrointestinal, mammary, and urogenital tracts are established before birth or early in life, then products will be developed to inoculate colostrum milk fed to calves at birth to create beneficial microbiomes. Once microbiomes are established, the modification strategy will be to displace or replace specific organisms in a priority order rather than replacing the entire microbiome. Proprietary microbial products will be used therapeutically to replace some antimicrobial products, and these may require a prescription from a veterinarian.

The dairy enterprise will utilize microbial additives for seeds, soils, crops, and irrigation water to improve soil health, boost crop yields, and protect water quality. Seeds will be coated with microbes that enhance soil fertility and improve yields without increasing chemical inputs (Broadfoot, 2016). In housing and milking facilities, microbial mixtures will enhance the quality of bedding materials, increase values of manure and welfare? How is a herd's health and performance affected by land where its feed is grown? What are the most important practices for caring for and managing herds?

Can we understand how cattle in a herd communicate to influence a herd's behavior, health, and productivity? Do cows signal to other cows their responses to personnel, housing conditions, feed, threats, and rewards? How does communication among cows differ among herds? Can we develop ways to communicate effectively with cattle? Many species secrete pheromones, but we are only beginning to identify the signaling chemicals in urine and other excretions of cattle (Archunan and Kumar, 2012). If we could identify and detect volatile or soluble signals in milk, urine, or feces that reflect various physiological or disease states in dairy cattle, this would be a valuable tool for managing herds.

It will be essential to engage scientists from public and private sectors to undertake this task. It will be necessary to develop ways of capturing data that are not collected routinely. For example, what percentage of herds use standard operating protocols for monitoring and recording health and disease events, and how well are these protocols implemented consistently within a herd? Do protocols for the same practices differ among herds? If so, do some protocols result in better outcomes? Are there electronic systems or software that monitor protocols routinely to verify compliance? Artificial intelligence systems used in other sectors will be modified and used to benefit the dairy sector in this area.

We need to look at the entire dairy enterprise when considering the herd as a superorganism. It will take partnerships among dairy farmers, dairy product companies, equipment manufacturers, input suppliers, scientists, veterinarians, and government agencies to conduct such studies. Support will be needed from experts in areas such as operations management, human sciences, and workforce development to understanding how training and recurring improvements in management affect a herd's overall performance.

We currently have more than 40,000 dairy herds in the United States and hundreds of thousands more in other countries, so there are plenty of opportunities to find herds for these studies. It will be important to select several herds within multiple independent areas that reflect differences in weather and climate, typical feedstuffs, types of facilities and housing, and production goals (e.g., conventional, organic, low input, grass-fed). In the end, we will learn much about primary factors that influence herd performance, productivity, and health and well-being, and this will be beneficial to feeding the world in 2067.

UNCERTAINTIES

Dairying has been a part of domestication of livestock for about 360 human generations (Hirst, 2017). The next 50 yr comprise about 2 generations, so it seems unlikely that dairying as we know it will be displaced by 2067. It is more likely that new technologies coupled with improved sustainability of farming practices will strengthen dairying and keep it positioned to provide dairy foods efficiently and sustainably.

Disruptive industrial technologies could alter dairying. A counterfeit of cow milk is being produced currently through industrial fermentation (http://www.perfectdayfoods.com/). The products being manufactured comprise plant-based sugars and fats, minerals, and proteins secreted by yeast that have been genetically modified by insertion of bovine genes. The challenge for manufacturers will be to produce products that mimic characteristics of cows' milk that make it broadly used in food products worldwide.

Changes in sources of energy could influence where dairy farms are located if energy cost is reduced substantially for desalination of seawater. The multi-national fusion project known as ITER (https://www.iter.org/proj/inafewlines) and now underway in France could provide a way for clean energy to be produced at a low cost. This could benefit dairy farms in coastal regions that are forecast to have inadequate precipitation in the next 5 decades (Figure 4).

Societal preferences will continue to influence food production including dairy farming, particularly as future generations become more displaced from ancestral connections to farming. Many concerns of consumers are focused on practices that they perceive to be unnatural, including confining cattle, overuse of pharmaceuticals, weaning calves shortly after birth, overuse of chemical fertilizers and pesticides, and contamination of streams and sub-surface water with livestock waste. Many of the practices that will be developed and implemented in the next 50 yr will ameliorate several of these issues and dampen concerns of consumers. There will be more zoning- and regulatory-based restrictions on farming, but demographic shifts to urban areas could also free up land resources for farming. Structural consolidation of dairy farming will continue, and the industry will become more vertically integrated than today.

CONCLUSIONS

The world faces a challenge in feeding its expanding population during the next 50 yr, and we forecast that dairying will meet this challenge by exploiting knowledge and technology to develop better dairy cows and

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