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INTERPRETIVE SUMMARY

A vision for dairy farms and cows in 2067. *Britt et al, page 0000.* During the next 50 yr global population will reach 10.4 billion and per capita consumption of dairy products will increase, driving upward demand for milk. Climate change will shift location of dairy farms to areas with adequate water, and dairying will continue to provide nutrients sustainably. Dairy cows will be healthier and milk yield will double. Technologies linked to epigenomics and microbiomics will be adopted along with increased automation and greater focus agroecology. Understanding of herd management will be improved by evaluating herds as superorganisms.

INVITED REVIEW: DAIRY FARMS AND COWS IN 2067

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

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ABSTRACT

Worldwide population in 2067 will reach 10.4 billion with 81% residing in Africa or Asia. 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 into more northern latitudes. Dairy consumption will increase because it provides essential nutrients more efficiently than many other agricultural systems. Milk production per cow will increase, reaching 25,000 kg/yr per cow in countries with advanced dairying systems. Genetic improvement will include emphasis on the coding genome and associated non-coding epigenome of cattle, and on microbiomes of microbiota of dairy cattle and farmsteads. Farm sizes will increase and there will be more 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 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 agroecology of dairy farms.

INTRODUCTION

Demand for dairy products and technologies will grow during the next 50 yr for two 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 B12 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 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 classical omnivore-based diets for maximizing capacity of crop lands to feed the greatest number of people while adhering to recommended agronomic practices for various classes of lands (Peters et al., 2016).

To supply increased demand for dairy products in developing countries, there must be a balance between imports and products produced within country. This provides opportunities for exporting countries to provide dairy products as well as dairy equipment and technologies to expand dairy farming in countries where suitable land resources exist (Gerosa and Skoet, 2012).

As demand for dairy products increases it is important to understand how dairy cows and farms will change during the next several decades to meet the demand. Our group of authors has been engaged informally for more than 2 yr with a specific focus on dairy cows and farms in 2067 -- primarily in developed countries with advanced dairy farm industries and technologies. We have developed a vision for modern dairy cows and farms for 50 yr in the future. In this forward-looking commentary, we also include a brief look at global dairy production.

POPULATION AND CLIMATE IN 2067

Population Demographics

The United Nations estimates that our world's population will grow from 7.6 to 10.5 billion between 2017 and 2067 (United Nations, 2017). This projection represents the median variant, between high (12.6 billion) and low (8.6 billion) variants. Asia and Africa will account for 93% of this growth (Figure 2). Latin America and the Caribbean, North America, and Oceania will grow modestly whereas Europe will decline in population. Half of the world's population in 2067 (5.2 billion people) will live in 10 countries, ranked by population: India, China, Nigeria, United States, Pakistan, Indonesia, Democratic Republic of the Congo, Ethiopia, Brazil and Bangladesh.

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.

Changes in climate will cause shifts in 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 farms in these areas will relocate to areas with more sustainable water supplies and adequate growing seasons. Areas most suitable for dairy expansion are in the upper Midwest and Great Lakes regions and into the central provinces of Canada. These areas are forecast to have adequate water resources and longer growing seasons in 2067.

DAIRY CONSUMPTION AND PRODUCTION

Worldwide, annual consumption of dairy products (fresh milk equivalent basis) averages about 87 kg per person based on extrapolations from Alexandratos and Bruinsma (2012). In developed countries, consumption currently averages about 200 kg/year per person compared with 55 per person in developing countries. This amount does not include butter, which is included as an animal fat in the food classification system used by the FAO.

Annual dairy consumption (skim milk basis) is estimated to increase to 119 kg per person worldwide by 2067. Increased consumption of dairy products coupled with increased growth in population translates into a need for approximately 600 billion kg more milk in 2067 than is produced today. According to FAO, dairy cows produce 82.4% of the world’s milk followed by buffalo (13.6%), goats (2.3%), sheep (1.3%) and camels (0.4%).

In 2014, an estimated 274 million dairy cows dotted the globe (FAOSTAT, 2017). To produce the estimated 600 billion kg of additional milk needed by 2067, an average dairy cow needs to double annual yield from 2,405 to 4,531 kg. This seems doubtful because many countries with lowest annual production per cow have the most cows (Figure 5). It is unlikely that yield will increase 10-fold during the next five decades in countries with lowest annual yields, so the needed milk or dairy products will most likely come from countries with highest current yields.

Countries with greater production levels per cow could meet much of the increased demand for dairy products without doubling production per cow. Fifteen of 20 countries that rank highest in total annual production of milk from dairy cows are located outside Africa and Asia and in regions where growth of populations will be modest or negative during the next 50 yr (Figure 6). Many of these countries are positioned to capitalize on growing worldwide demand for dairy products.

We projected that dairy cows will produce approximately 25,300 kg per cow annually by 2067 in the United States (Figure 7). For this projection, historical yield data from USDA were subjected to linear and exponential extrapolation to 2067 and then our group discussed these trend lines and opined that average annual yield in 50 yr would be at 25,300 kg, approximately midway between the linear and exponential extrapolations. From 1945 to 2015 milk yield per cow in the USA increased 5.2% per yr (113 kg/yr). The trend lines in Figure 7 reflect increases of 1.3% and 129 kg per year (linear) and 3.5% and 412 kg per year (exponential). Our opinion is that yield will grow by 3.0% and 300 kg per year. If annual production per cow reaches this level, number of cows needed to meet domestic consumption in the United States in 2067 will drop below 5 million. As production per cow increases, there is an opportunity for the United States and other exporting countries to increase exports to maintain cow numbers nearer to today’s levels.

We do note that gains in milk yield may be tempered by greater focus on milk solids production. Selection for more milk solids is consistent with annual commercial disappearance of dairy products, particularly butterfat (see file: Commercial disappearance for dairy product categories (monthly) available at https://www.ers.usda.gov/data-products/dairy-data/). Domestic consumption currently favors increased yield of fat and protein within a lower volume of milk. Most genetic selection indexes currently place positive emphasis on fat and protein yield with no weight or a negative weight on milk yield. Milk yield will continue to increase as a correlated response to selection, but volume may increase at a slower rate with greater emphasis on milk solids. A greater emphasis on milk solids may accelerate a shift to breeds that produce higher solids percentages.

Exports

The challenge for dairy exporting countries and regions such as the United States, New Zealand, and EU will be to develop products that provide affordable dairy-based nutrients to meet needs of children and adults in countries in which demand will increase. Meeting this need will require a different strategy than 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. Projections show that 31% of the population in Nigeria in 2067 will be less than 15 yr of age compared with 17% in the United States. In contrast, 24% of the population in the United States will be 65 yr or older compared with only 5% in Nigeria

(De Wulf, 2016). Thus, population demographics of export markets may differ substantially from those of exporting countries and this difference will drive the need to produce country-specific export products (Odle et al., 2017).

COWS OF THE FUTURE

Dairy cows of the future will produce more milk solids, have relatively smaller environmental footprints, be healthier and have genetic characteristics that fit their climatic locations. Specific lines within major dairy breeds will be developed efficiently through genomic selection to fit various dairy sectors worldwide (Boichard et al., 2015). If major genes that provide greater heat tolerance and enhanced health are 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 indexes. Trans- 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, rate of genetic progress for several traits in Holsteins accelerated (Garcia-Ruiz, 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 and associated traits. 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, 2017).

Genetic progress also will benefit from reduction in generation interval associated with genomic testing and use of reproductive technologies. Since 2009, generation interval for bulls entering AI in the United States has dropped from approximately 7 to 2.5 yr. (Garcia-Ruiz, 2016). This interval is approaching the theoretical limit for non-surgical 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. It is possible for generation interval to 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 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 from 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 and Welfare. Selection for health- and environmental-related traits will expand as new genomic selection indices are added (Cole and VanRaden, 2017). Some major genes may be moved within or 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 move quickly 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; Parker-Gaddis et al., 2014; Miglior 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 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, two 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 five 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 impacted less by metabolic changes during the postpartum period.

One genetic opportunity that has global appeal is development of cattle that are resistant to major infectious foreign diseases such as foot and mouth disease (FMD) and endemic diseases like Leptospirosis, IBR and BVD. These diseases affect cow health and may interfere with international trade. Within five decades, there is a good possibility that some of these diseases will be eliminated through genomic selection and other technologies.

Proprietary lines of dairy cattle will be developed by commercial businesses that have access to genomic information not in the public domain. These lines will have phenotypes that make them profitable for dairy farmers by production of unique or therapeutic milk products, greatly improved feed efficiencies, or other characteristics. These lines will have intellectual property protection that will limit the sale of breeding stock from farms.

The importance of specialized dairy cattle lines in the future will lead to a change in the way that genetic resources are marketed from breeding companies. The primary product will expand from semen to fresh or frozen embryos that will be produced through cell culture techniques maintained for each line. This will essentially move genetic mating decisions to the IVF laboratory rather than on the farm, but it will also increase greatly the types of products produced by the dairy genetic industry.

Understanding Epigenetic Effects

Significant improvements will occur in understanding roles and importance of non-sequence based features of the dairy cattle genome and how these affect gene function in response to environment. Classically this has been referred to as epigenetics and has largely focused on methylation of DNA or acetylation of histone proteins. Now we know that there are many DNA sequences that are transcribed into RNA that acts as a regulator of gene action rather than a template for protein synthesis. So the focus of epigenetics has broadened to include additional mechanisms such as transfer of RNA between cells (Macaulay et al., 2016) and regulation of genes by non-translated RNAs (Yang et al., 2017).

Intervals between environmental events and subsequent epigenetic responses may be as long as months or years. Here we refer to such displaced responses as epigenetic effects because of their latent temporal nature (Humblot, 2011; Sinclair et al., 2016). One example of an epigenetic effect is how body condition change during 3 to 5 wk postpartum affects conception rate at 12 wk postpartum. Holstein cows that lost more body condition during 5 wk postpartum had lower fertility at first AI at 83 days postpartum and this led to the Britt Hypothesis (Figure 8) that postpartum BW loss exerted an adverse effect on the developing follicle or its oocyte (Britt, 1992). A subsequent experiment with 1887 Holstein cows found that cows gaining body condition during 3 wk postpartum had a timed-AI pregnancy rate of 84% compared with 38% and 25% for cows that maintained or lost body condition. (Carvahlo et al., 2014). This fertility response illustrates the time lag between an event (loss of body condition) and it outcome (conception rate). Lucy et al (2014) suggested that effects described by the Britt Hypothesis be extended to the oviduct and uterus because of their responses to BW loss during the postpartum period.

There are numerous examples of such latent responses in dairy cattle. Heifer calves that gain more weight during the first 2 mo of life produce more milk in their first lactation about 2 yr later (Soberon et al., 2014), apparently because more gain in early life induces growth of more mammary epithelial cells that later produce more milk (Soberon and Van Amburgh, 2017). Holstein cows milked more frequently each day during the first 3 to 6 wk postpartum and then at a lower frequency during the remainder of lactation produce more milk during the remainder of lactation than control cows milked at the lower frequency throughout the entire lactation (Bar-Peled et al., 1995; Hale et al., 2003).

The ovarian follicle reserve is established during fetal development, and cattle with an optimal ovarian reserve have better reproductive performance (Mossa et al., 2012; Jimenez-Krassel et al., 2017). Husbandry practices, disease and environmental conditions can affect this reserve. For example, restricting weight gain in early gestation in pregnant cows reduces 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 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 indentifying and understanding microbiomes (genomes) of organisms in cattle fed and managed under various conditions (Deusch et al., 2015). For example, the fecal microbiome of beef cattle differs 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 ratio of the two 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. So 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 supports that it begins to be established by 2 d after birth (Yanez-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 Opsta and Bordenstein, 2017). It may be possible to utilize genomic selection to manipulate gastrointestinal microbiome to improve feed utilization and health of dairy cattle.

Microbiomes of mammary (Oikonomouj 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, managing the microbiome may become a key aspect of herd management.

Biological Limits.

An often-asked question by scientists, farmers and consumers is “Are we reaching the biological limit in milk yield and production traits?” To address this question, our group examined data from top-yielding cows in the United States and compared yields among cows of the same breed in the United States. Top individual cow records produced during the last decade were 10 to 14 SD units greater than the average yield per cow in 2014, indicating that the potential for increased yield is substantial. Similarly, we looked at US crop yields and found that top yields for maize and soybeans in 2014 were 7 to 9 SD units greater than average yields

(Lobell, 2014). Therefore, imminent biological limits do not seem to be restraining output per cow or per hectare.

ORGANIZATION AND MANAGEMWENT OF DAIRY FARMS OF THE FUTURE

Dairy farming enterprises of the future will be larger and utilize lateral integration to house and manage classes of cattle within enterprises. Robotics, sensors and automation will replace many manual labor activities and enhance agro-ecological practices for dairy enterprises. Crops and feeds will require fewer inputs such as fertilizers and pesticides and will be more digestible. Greater focus will be placed on systematically managing the epigenome and microbiome to enhance animal health and productivity. Facilities for housing dairy cattle will be modified to allow dairy cattle to express natural behaviors. The herd will be managed as a superorganism.

Dairy Farm Sizes and Organization

Dairy farm enterprises will continue to increase in scale to optimize efficiency and lower cost of producing milk (MacDonald and Newton, 2014). Limits on size will be affected by zoning and environmental regulations and proximities to heavily populated areas.

Dairy enterprises will move toward specialization in housing and managing various groups of cattle (Figure 9). Two key components of specialization will be shared transition facilities and shared feed centers. Cows in a shared transition facility will be milked 3- to 4-times daily and managed to minimize impacts of transition on health and well-being. Feed centers will harvest and store crops from land occupied by dairy enterprises and other farm land and deliver feeds to various units using driverless, automated equipment. Relative cost of feed will be reduced because of the efficiencies of scale

Dairy beef will increase in importance because its production generates about one-third of the green house gas equivalents per unit weight of product as traditional beef production (Opio et al., 2013). Cows with lower genomic ranks in herds will be inseminated with gender-selected sperm from beef sires or will receive terminal-cross embryos from beef-breed donors. This will increase 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.

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 pasture-based grazing or local production. Other small farms may produce milk with proprietary therapeutic products.

The shared resource model (Figure) will reduce construction and operating costs because specific milking and housing facilities will be identical, using common 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 a different one during different lactations.

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. This integrated system will contribute significantly to improving sustainability of the dairy enterprise from field to farm gate and beyond.

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-D 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 also will 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, feed will be loaded, mixed and delivered by driverless vehicles, and livestock waste and waste water will be processed automatically to produce energy, fertilizers, other co-products, and clean water. 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-utilized into 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 management practices that benefit animal health, welfare and productivity through controlling effects of epigenomics and microbiomics in herds. This will be guided by improved understanding of temporal cause-and-effect relationships that lead to improvements in animal health and welfare; more efficient utilization of land, crop and byproduct resources; and improvements in sustainability. Practices and protocols will be guided by artificial intelligence systems that mine data from the entire farm enterprise.

Epigenetic management will be focused on individual animals, and individual field crop areas that will be harvested at the same time. For example, cows that are expected to be exposed to heat stress that raises their body temperature to a critical level may receive certain dietary supplements while being milked robotically or during feeding in dry cow groups. Crops that are expected to be stressed by too much or too little water during specific growing stages will be treated with different inoculants at harvest and storage to improve digestibility or nutrient quality.

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 that microbiomes of gastrointestinal, mammary, and urogenital tracts are established before birth or early in life, then, products will be developed to inoculate colostral milk fed to calves at birth to create beneficial microbiomes. Once microbiomes are established, the strategy to modify them 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 veterinary prescription.

The dairy enterprise will utilize microbial additives for seeds, soils, crops, and irrigation water to improve soil quality, boost crop yields and protect water quality. Seeds will be coated with microbes that enhance soil health and improve yields without increasing chemical inputs

(Broadfoot, 2016). In housing and milking facilities, microbial mixtures will enhance quality of bedding materials, increase values of manure and wastewater, and improve natural biodiversity of the farmstead.

Feeds

Increased focus on improving digestibility of feeds and on utilizing crops that sustain soil fertility and health will enhance agro-ecosystems on dairy farms. Progress will continue in development of alfalfa and other forages that have less lignin and more starches (Combs, 2016). Drought- and salt-tolerant varieties will increase in importance as climate changes and irrigation increases. High yielding perennials including perennial maize (Murray and Jessup, 2014) and hybrid canes (Głowacka et al. 2016; Burner et al, 2017) that have high sugar contents will be introduced for production of silage. New feeds or feed supplements also will be produced from microalgae (Costa et al., 2016). There will be increased emphasis on reducing amount of chemical fertilizers and pesticides applied to cropland through development of crops that need less fertilization and through broad use of precision farming technologies that match application rates with fertility at square meter-level specificity.

Facilities to Benefit the Cow's Natural Behavior and Health

Confinement facilities restrict natural behaviors, limit expression of estrus, and contribute to lameness and other health problems that impair well-being of cattle (Dobson and Smith, 2000; von Borell et al., 2007). These effects are attributable largely to cows spending most of their standing or walking time on concrete alleys and walkways rather than on surfaces that provide more cushioning and comfort. Cows learn to behave differently on concrete than on natural surface; for example they display less mounting and standing activity during the same estrus on concrete than on dirt (Britt et al., 1986).

Facilities in the future will be designed and constructed to benefit cows in confinement. Alleys and walkways will be constructed with laminates that combine underlying strength and durability of concrete with overlying flexible polymers strengthened by carbon materials. Cows may move regularly through covered exercise arenas in their daily routines and sensors will detect lameness earlier than today's manual scoring methods. Stall and loose housing facilities will be cleaned, bedded, and managed by robotic equipment to collect waste from bedding surfaces, tend the bedding substrate and provide fresh material as needed.

Facilities will provide ways for early postpartum cows and newborn calves to interact for an extended period after birth. Most interactions between cows and their calves will be controlled through electronic sorting systems that fit into the natural flow of cows in the facilities.

HERDS AS SUPERORGANISMS

The term superorganism typically refers to a colony of animals, such as bees or termites that function as a unit (hive or nest) and that has divisions of labor among members of the group (Seeley, 2010). Such groups share sources of food and living conditions and are exposed to the same diseases and environmental conditions. Cattle in dairy herds share feed and living conditions and are exposed to diseases as a group. A herd should be viewed a superorganism and be considered as an observational unit in developing more knowledge about herd management.

A herd is the central production and economic unit of dairy farming, but we lack understanding of why herds differ in productivity, animal well-being and economic viability. Historically, animal scientists have practiced reductionist-oriented research, moving from studying complete organisms to studying an organism's systems, organs, cells and genes. Reductionist research does not provide important data about what accounts for differences among herds.

We need studies focused on herds as experimental units to understand how environment, operational practices and interactions among animals affect a herd’s performance. For example, why do dairy herds located in common physiographic areas and feeding similar diets differ in productivity, health and animal 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, are there some that result in better outcomes? Are there electronic systems or software that monitor protocols routinely to verify compliance?

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. There will need to be support 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, etc.). In the end, we will learn much about primary factors that influence herd performance, productivity, 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 its position of providing dairy foods efficiently and sustainably.

Disruptive industrial technologies could alter dairying. A counterfeit of cow's 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 sea water. The multi-national fusion project known as ITER and now underway in France could provide the way for clean energy at a low cost https://www.iter.org/proj/inafewlines. This could benefit dairy farms in coastal regions that are forecast to have inadequate water resources in 2067 (Figure

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 also 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 more productive and sustainable dairy farms. Discoveries and application of new practices in areas such as genomics, microbiomics and intelligent systems will be among key avenues for boosting milk yield of dairy cows and milk output from dairy farming systems. Our vision is that dairying in the future will reflect sustainable intensification that benefits animals, agroecosystems and mankind through production of key nutrients for human consumption.

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FIGURE LEGENDS

Figure 1 Square meters of land required to produce 1 gm of protein from various crops or production systems. Data from Clark and Tillman (2017) and graph modified from Roser and Ritchie (2017).

Figure 2. Estimated population of world's regions from 2017 to 2067. Raw data downloaded from United Nations (2017).

Figure 3. Deviations in average global temperature from average temperature for 1901 to 2000. Source of data: NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published July 2017, retrieved on July 27, 2017 from http://www.ncdc.noaa.gov/cag/.

Figure 4. Projected relocation of dairy farming from US regions with shortages of water to US 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 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 by permission (Roy et al., 2012).

Figure 5. Number of cows (n, millions) and average yield per cow in kg/yr for the 10 countries with the greatest number of cows in the FAO database for 2014. These countries comprise 150 million milk cows, about 46% of the world's inventory.

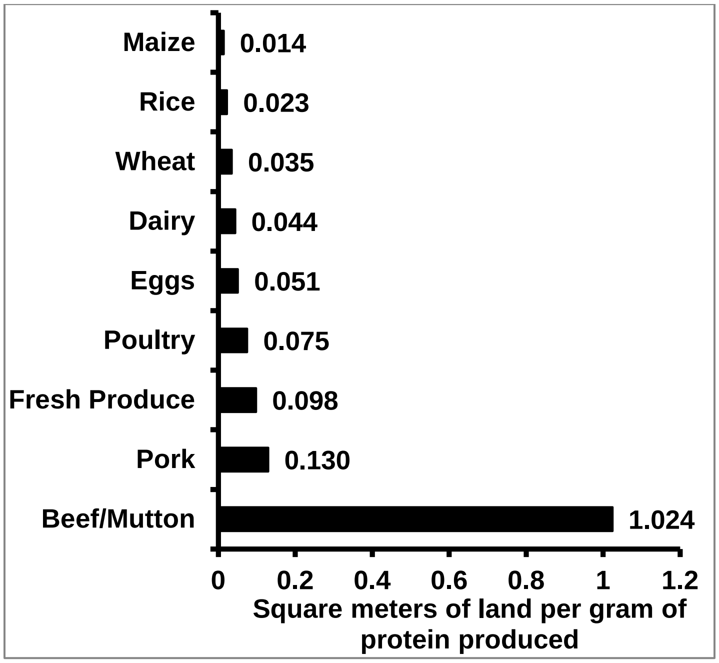
Figure 6. Annual yield of milk per cow and percentage of world's cow milk produced by the top 20 producing countries in 2014. These countries produced 74.4% of world's cow milk. Closed circles represent countries in Africa or Asia. Country codes are from http://www.fao.org/countryprofiles/iso3list/en/.

Figure 7. Forecasted change in milk yield of USA dairy cows in the next 50 yr. Actual data from USDA sources (heavy black line) were extended through linear and exponential trend lines using Microsoft Excel®. Our group of authors discussed these trend lines and agreed on a likely level of production (star on right vertical axis).

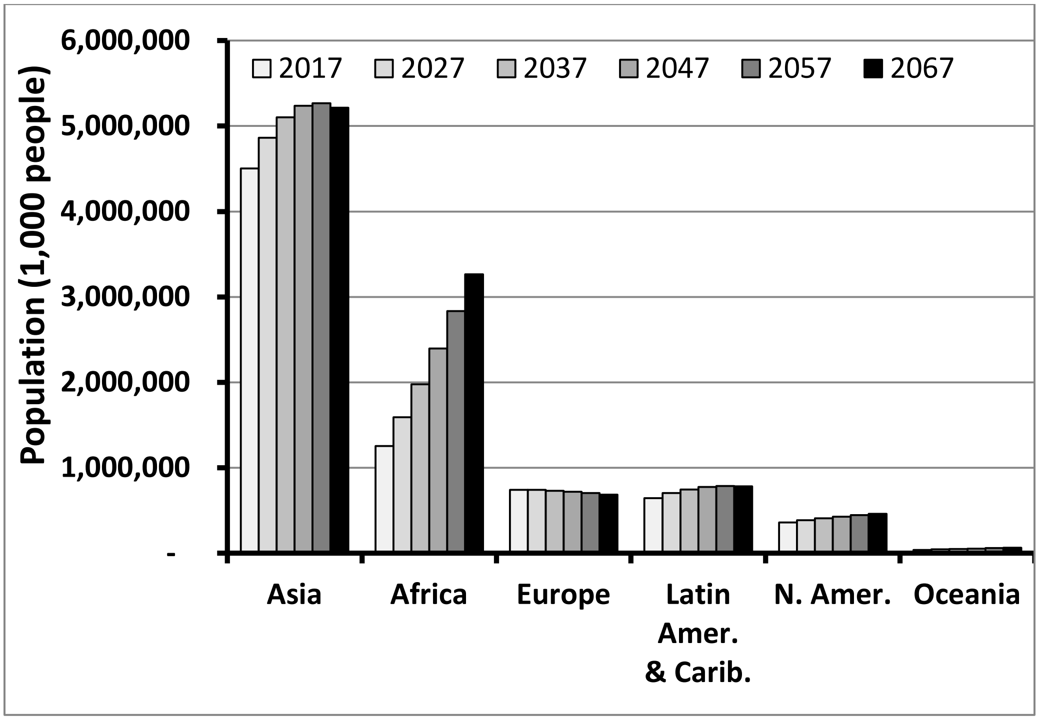
Figure 8. Example of an epigenetic-type effect on the developing bovine oocyte that is subjected to changes in energy balance and other adverse environmental conditions during the transition period in dairy cows. The oocyte is activated about 21 days prepartum and ovulated about 80 days postpartum. It 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).

Figure 9. Model of organization of dairy enterprises of the future. Cows will be fed and managed in a transition facility and milked 3- to 4-times per day. Cows will then move to Milk Cow units for voluntary milking in robotic systems. Calves, heifers, dry cows and dairy beef will be managed in separate shared facilities. Feed will be stored and mixed in feed centers that serve multiple locations. This organization model would serve a single large dairy enterprise or multiple smaller dairy enterprises.

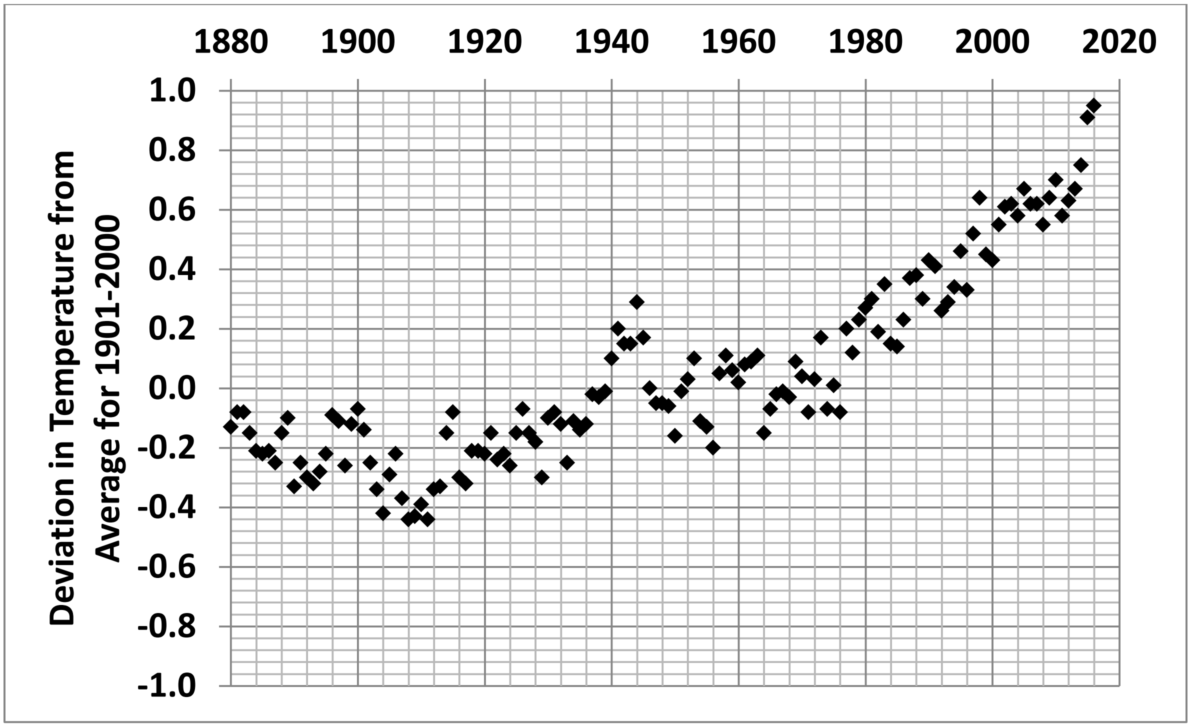
Britt, Figure 1



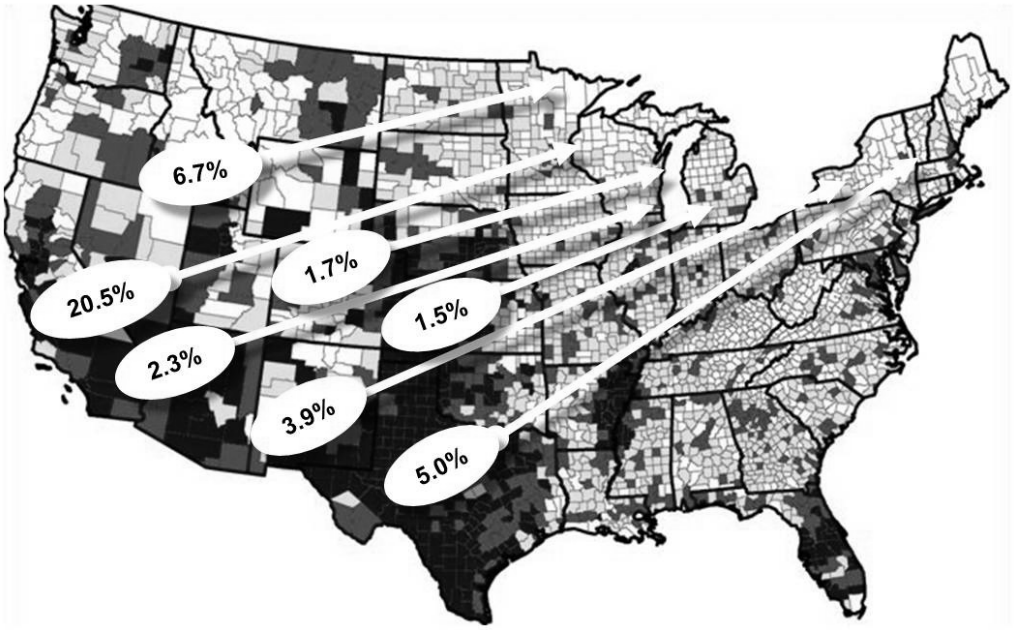
Britt, Figure 2



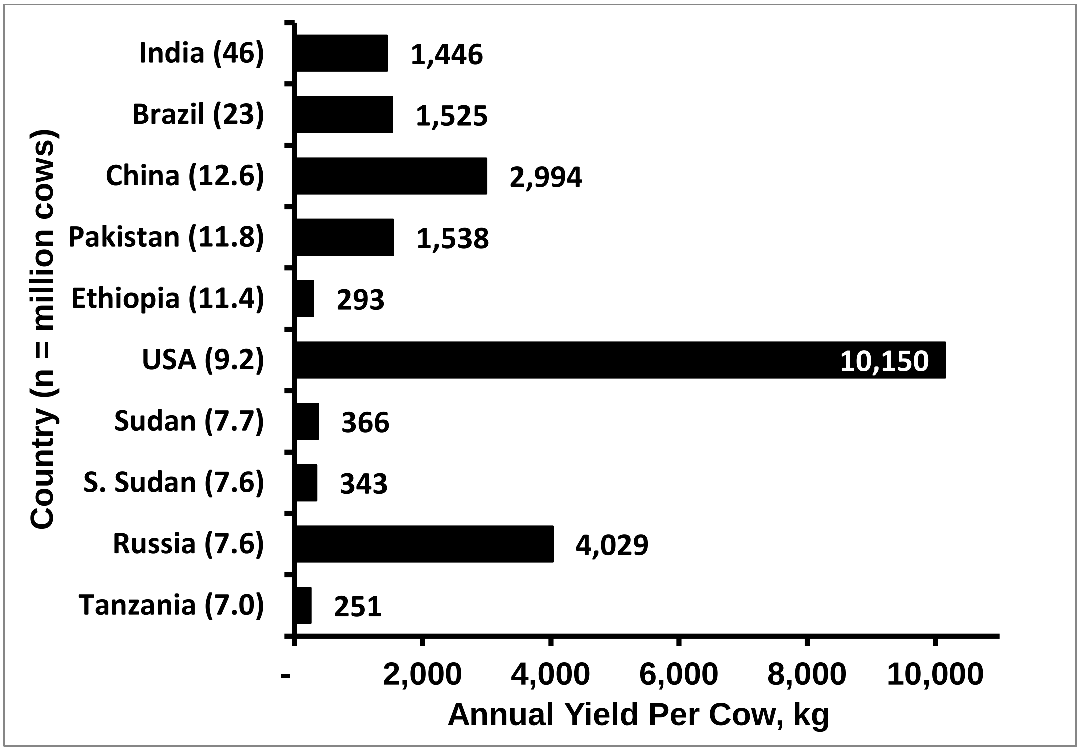
Britt Figure 3



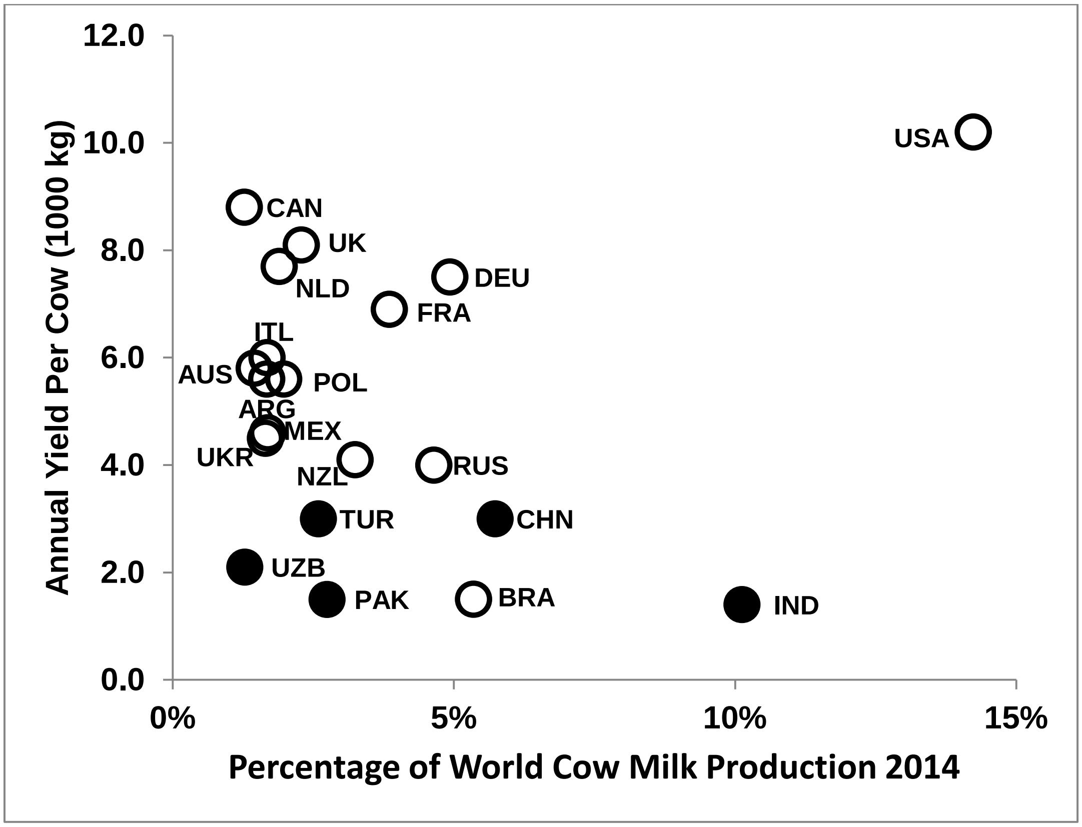
Britt Figure 4



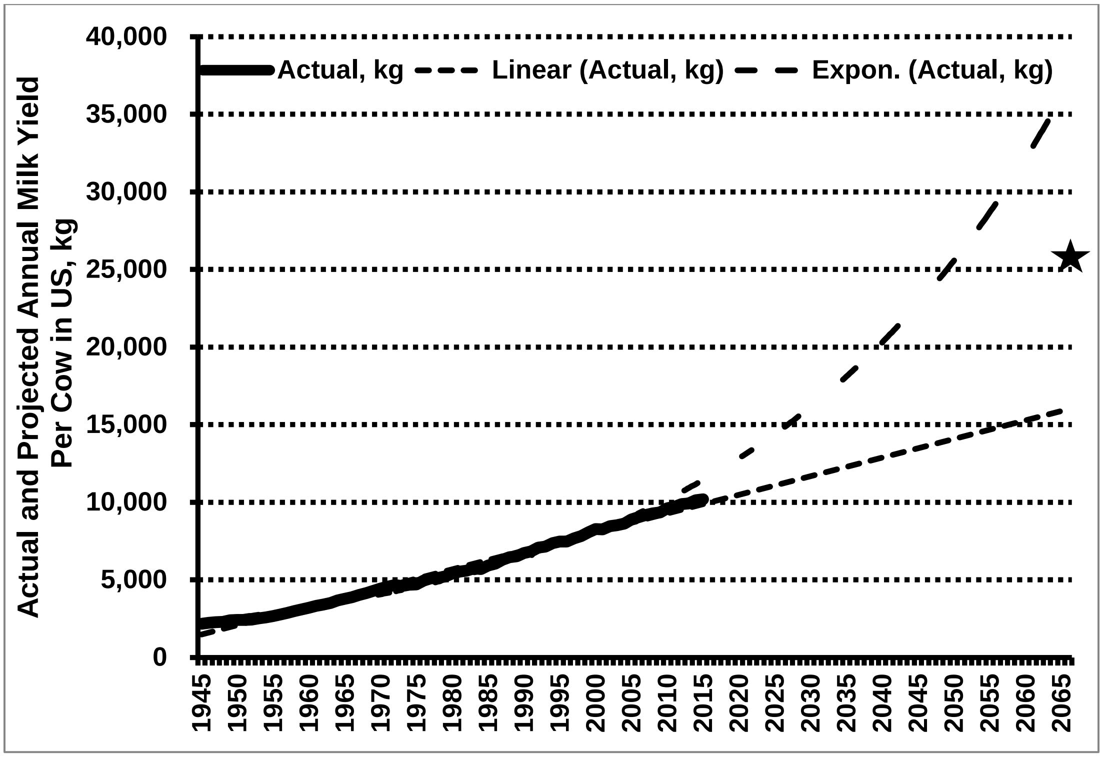
Britt, Figure 5



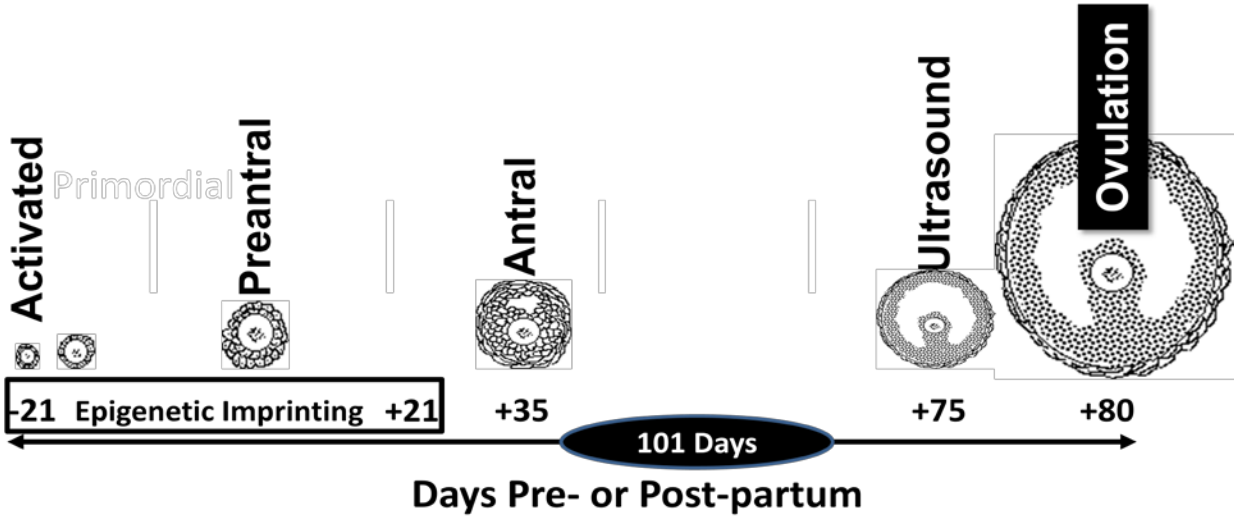
Britt Figure 6



Britt, Figure 7.



816 **Britt Figure 8**



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Britt Figure 9