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Review: Perspective on high-performing dairy cows and herds

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A B S T R A C T

Milk and dairy products provide highly sustainable concentrations of essential amino acids and other required nutrients for humans; however, amount of milk currently produced per dairy cow globally is inadequate to meet future needs. Higher performing dairy cows and herds produce more milk with less environmental impact per kg than lower performing cows and herds. In 2018, 15.4% of the world's dairy cows produced 45.4% of the world's dairy cow milk, reflecting the global contribution of high-performing cows and herds. In high-performing herds, genomic evaluations are utilized for multiple trait selection, welfare is monitored by remote sensing, rations are formulated at micronutrient levels, health care is focused on prevention and reproduction is managed with precision. Higher performing herds require more inputs and generate more waste products per cow, thus innovations in environmental management on such farms are essential for lowering environmental impacts. Our focus is to provide perspectives on technologies and practices that contribute most to sustainable production of milk from high-performing dairy cows and herds.

Implications

High-performing dairy cows produce four-fold as much milk as an average world dairy cow. These cows are in herds that provide balanced nutrients required for high levels of milk output. These herds utilize modern dairy management practices, incorporate high-quality genetics in their breeding programs, ensure cows have comfortable environments, provide high-quality health care, and manage reproduction efficiently. These herds attempt to minimize environmental impacts through using best practices for producing crops and managing water and manure. Cows in these herds are more likely to be confined in modern barns with limited access to pasture.

Introduction

Dairy products provide essential amino acids and nutrients, and diets enriched with dairy products reduce stunting in children and increase growth rates (Food and Agriculture Organization of the United Nations, Global Dairy Platform, and International Farm Comparison Network Dairy Network, 2020). An important question is what daily diet would feed the most people from arable land globally. This question was addressed by Peters et al. (2016), who examined eight different diets, ranging from a purely vegan to an extensive omnivore diet. Each diet was required to provide essential amino acids and micronutrients that humans must consume. The diet that fed the most people with the least amount of

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land was a vegan diet supplemented with dairy products. Annual milk supply globally must increase to an estimated $1.12 \cdot 10^{12}$ tons by 2070 (extrapolated from Alexandratos and Bruinsma, 2012), and this demand will be met through sustainable intensification (Baulcombe et al., 2009; Godfray et al., 2010; Balmford et al., 2018; Britt et al., 2018).

Our focus in this perspective is on high-performing dairy cows and farms globally, particularly on their role in providing nearly half of the global milk supply, their challenges with volatility in the global milk market, their efforts to improve sustainability, and their success in enriching cows' environments, adopting and utilizing advanced genetics, improving reproduction, preventing health problems and feeding dairy cows successfully. There are $265 \cdot 10^6$ dairy cows globally according to FAOSTAT 2018 database. We calculated intensity of production per cow by dividing each country's portion of the global milk supply by that country's portion of global dairy cows (Fig. 1). To be included in analyses, a country must have had at least 1% of the world's dairy cows (n = 21) or produced at least 1% of global milk production (n = 14). Countries with least intensity of production (<1.0) were in East Africa (n = 6). South Asia (n = 3), South America (n = 2) and Western Asia (n = 1). These countries held 52.6% of the world's dairy cows and produced 25.3% of the world's milk from dairy cows. Cows in these countries are mostly in smallholder confined herds and fed byproducts from plant crops (Bateki et al., 2020). Countries with greatest intensity of production (>2.0) were in Europe (n = 8), North America (n = 2), East Asia (n = 3), West Asia (n = 1), South America (n = 1) and Oceania (n = 1). These countries held 15.4% of the dairy cows and produced 45.4% of world's milk from dairy cows. Annual yield of milk solids (fat + protein) per cow continues to increase in multiple modern dairying countries (Fig. 2).

Perspective on sustainable high-performing dairy cows and herds

Sustainability of dairy farms depends on multiple factors (Table 1). There is not a definition of sustainability that fits all dairy farms across the globe, nor is there a single farming system that is more sustainable than alternative systems. Intensity of production is linked positively to higher environmental sustainability among several agricultural sectors. Balmford et al. (2018) studied dairying in the UK, wheat production in the EU, rice production in China and beef production in Brazil to assess environmental sustainability. In all cases, intensive systems were more sustainable environmentally as measured by greenhouse gases (**GHGs**) output, N loss into the soil, P loss into the soil, soil loss (erosion) and loss of habitat. As global population grows, amount of current arable land to produce food or feed will decline on a per capita basis; however, climate change could open more land at northern-most latitudes for producing crops (Hannah et al., 2020). Sustainability of dairying in some regions may change as climate change affects availability of water and crop production (von Keyserlingk et al., 2013).

Sustainable high high-performing dairy farming systems

High-performing dairy herds around the globe have many similarities, including breeds of cattle, use of modern technologies, veterinary care, dairying equipment and record systems. They face similar challenges, such as volatility of prices received for milk. Over the period from 2007 through 2019, there was a 79% difference in average inflation-adjusted prices paid monthly to farmers in the EU and UK for 100 kg of milk (Fig. 3). This volatility in Europe and elsewhere has led to an increase in average herd size. Smaller herds are unable to compete economically with larger herds when prices received are below cost of production, and cows from smaller herds move to larger herds. For example, average cows per herd increased 2.7-fold in New Zealand between 1991 and 2019, during a period when the country's total dairy cow herd increased 2.1-fold. As cows from smaller herds move into larger herds, yield per cow increases (Fig. 4).

Factors affecting sustainability

Sustainability of dairying depends on several issues, including cow welfare, dairy farming scale and resources, access to milk markets and dairy product portfolios (Table 1). Dairy farmers, their advisors, their dairy supply chain, their milk buyers, consumers, and policy makers should develop scorecards to monitor dairy

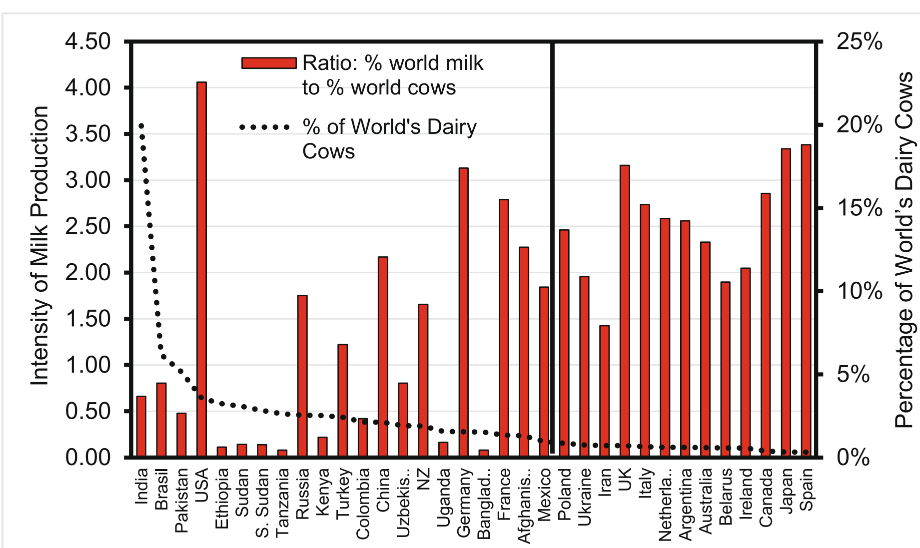

Fig. 1. Columns show intensity of milk production for countries of the world that had at least 1% of all dairy cows (left panel) or produced at least 1% of all cow's milk (right panel) in 2018. Dotted line shows percentage of world's dairy cows for each country. Intensity is defined by the ratio of a country's portion of global milk production to its portion of global dairy cows. Milk and cow data downloaded from FAOSTAT 2018 database. Data used for analyses included 77.8% all dairy cows and 86.5% of all cow's milk in the world.

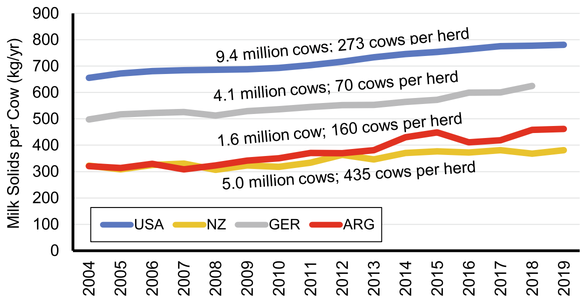

Fig. 2. Trends in yields of milk solids, current number of dairy cows (2019) and dairy cows per herd (2019) in Argentina (ARG), Germany (GER), USA and New Zealand (NZ). Long grazing seasons in Argentina and New Zealand provide vast majority of feed. Stored feeds comprise the primary sources of DM in Germany and USA. Data are from each country's governmental data site for dairy farm records.

farming sustainability specific for their regions or countries, because many aspects of sustainability differ among geographic and climatic regions. Does dairy herd size or milk yield per cow influence sustainable welfare of dairy cows? There is scarce evidence that larger farms provide poorer care or welfare than smaller farms, but group-size for cows should be managed carefully to avoid disturbing social orders among cows. Gieseke et al. (2018) evaluated dairy herds housed in freestalls in Germany and concluded that husbandry had a greater effect on welfare than number of cows per group. Beggs et al. (2019) studied Australian grazing herds and found that herd size did not affect lameness, mastitis, somatic cell count (**SCC**) or on-farm mortality. They reported that larger herds were more likely to use standard operating procedures, train farmworkers to improve consistency, have electronics for cow identification, use in-line systems for monitoring milk yield and mastitis, use anesthesia/analgesia for painful procedures and have a hospital pen where cows receive specialist attention.

Enrichment of environment for housed dairy cows

High-performing cows in dairy herds in northern latitudes are often housed part- or full-time. Comfortable stalls and flooring and enhanced lighting in dairy barns improve animal welfare. Cows on concrete floors are less willing to mount other cows in estrus (Britt et al., 1986). Concrete alleys and walkways are preferably covered with rubber mats providing a softer, non-slip surface. Use of LED lighting in feeding areas ensuring 16 h of light per day increases feed intake and milk production (Dahl et al., 2000). Multiple watering troughs in pens limit adverse impact of dominant cows on water intake by others (Sova et al., 2013). Clean and properly sized freestalls with deep sand increase resting time and cleanliness and decrease lameness and mastitis (Cook 2020). Well-positioned rotary brushes result in cleaner cows, stimulate blood circulation, and help satisfy natural grooming behavior (Goncu et al., 2019). Barns that incorporate sensors and automated ventilation systems with retractable curtain walls and fans, with or without water sprinkling overcome heat stress (Jones and Kammel, 2017). Innovative deep bedded compost barns enhance cow lying behaviors (Leso et al., 2019). Exercise areas are beneficial, particularly outside at pasture (von Keyserlingk et al., 2017).

In response to public opinion in some regions such as Sweden, farmers are required to provide housed cows with daily grazing seasonally. Cows that graze continuously have fewer incidences of subclinical mastitis, lameness, culling and mortality (Arnott et al., 2017; White et al., 2002), but may have more internal parasitism, malnutrition, and delayed onset of postpartum estrus (Mee and Boyle, 2020). Intensive grazing requires higher fertilizer use, thus raising concerns about loss of nitrogen and phosphorus into surface- or groundwater (Pinxterhuis et al., 2015; Bryant et al., 2020). Another forthcoming challenge for seasonal grazing, particularly in Europe and North America, is rising temperatures during grazing seasons that will cause dairy cows to be more heat-stressed during summer (https://www.eea.europa.eu/data-and-maps/indicators/global-and-european-temperature-10/assessment).

Advanced milking systems for high-performing cows and herds

Milking parlors have evolved to linear or rotary platforms accommodating up to 120 cows at once. Vacuum teat cups are attached manually, which is physically intensive requiring tedious attention to detail. There is increasing popularity of robotic milking systems, with an estimated 35 000 robots in use globally (John et al., 2016). Cows are enticed to enter robots voluntarily to gain access to feed, then electronic sensors control robotic arms that

Table 1
Examples of expectations, problems, issues and potential mitigations for sustainable high-performing dairy cows and herds in the future.

Focus	Expectations	Examples of problems and issues	Examples of mitigation
Cow welfare	• Unlimited availability of feed & water • Display normal behavior • Free from fear or pain, clean, comfortable • Minimal production-related diseases	• Mismatch of cow's genetics & herd's environment • Environmentally induced behavioral anomalies • Cow movements that disturb social orders & poor husbandry • Inadequate surveillance and treatment	• Precision diets, adequate space of water and feed bunks per cow • Automatic tracking & separation of cows; big data • Smart housing: clean, comfortable, temperature control & lighting • Efficient diagnostics, bio-therapeutics
Farm resources	• Land, transportation infrastructure & internet • Water, forage, feed, wastes & lower climate impacts • Access to input/output supply chain • Labor supply & management • Financial resources	• Climate change; access to water and poor connectivity • Feed wastage & poor manure & nutrient management • Access to inputs, processors, and consumer markets • Poor communication, delegation & rewards for employees • Inadequate return on investment	• Lower environmental footprints through management & technology • Farm-to-farm collaborations in crop production & waste management • Farm & herd located in active milk producing area • Staff training; automation for drudge jobs; praise • Entrepreneurial sharing of risks & rewards; research & development
Milk market	• Efficient market regulation • Payment more than cost of production • Consumer perceptions	• Insufficient producer control • Disruptions in supply chain to consumers • Undersupply of local milk	• Greater collaboration • Effective innovations & regulation of supply chains • Education; ethical governance
Dairy products	• Liquid • Cheese, butter • Powder; byproducts (e.g., whey)	• Improper storage of products • Seasonal variations in fat & protein • Surplus production & poor distribution systems	• Process for longer shelf-life • Balanced use of milk constituents • Objective regulation & management of dairy supply chain

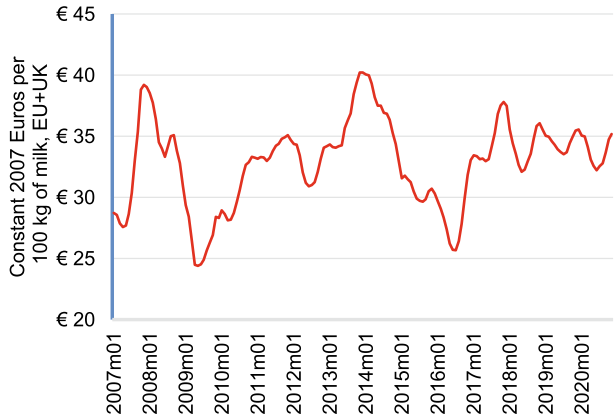

Fig. 3. Volatility in prices paid to dairy farmers for milk in the EU and UK from 2007 through 2019, adjusted to 2007 Euro equivalents to account for inflation. There is a 79% difference in prices paid after adjustment for inflation. Retrieved on 18 January 2021 from https://data.europa.eu/euodp/en/data/dataset/eu-milk-market-observatory-eu-historical-prices/resource/f05af922-3f35-40c3-8071-e419dd082a8d.

clean and stimulate the teats before attaching teat cups. Vacuum level, pulsation and cup removal are automated for each individual teat to avoid tissue damage. Abnormal milk is detected electronically and discarded.

Precision farming with artificial intelligence and Big Data

Precision farming focuses on using sensors and artificial intelligence to guide management of herds and farms. For an individual cow, micro-chips can store data about owners, location, genetics, reproduction, lactation, health care and disease. The social contract between dairy farmers and their cows requires using such advanced technologies to ensure well-being of cows. Artificial intelligence integrates eating, rumination, walking, resting, and body temperature to identify cows that are at greater risk of disease (Stevenson et al., 2020). Social network analysis will generate alerts for detection of atypical behaviors associated with ill-health (Vimalajeewa et al., 2019). Data collected from many different farms permit scientists and policymakers to address concerns around food provenance, welfare, influence of climate on food production, soils, pests, diseases, and impacts of different farming practices on ecosystems and environments (Eastwood et al., 2019).

Reducing impact of dairy farms on environment and climate

Advanced dairy farming globally has seen remarkable sustainable intensification to produce milk efficiently. Dairy farms in 2017 in the US produced 1 ton of milk with 25.2% fewer cows, 17.3% less feed, 20.8% less land, and 30.5% less water than in 2007 (Capper and Cady, 2020). Even so, dairy systems impact the environment by emitting GHGs, require blue water and loss of habitat for feed production, and use of water for milk production and processing that leads to water contaminants including N and P (Naranjo et al., 2020).

Greenhouse gas emissions

Anthropogenic GHGs are main drivers of climate change. Global livestock accounts for 14.5% of total GHGs (Gerber et al., 2013), and dairy as a subset accounts for approximately 20% of livestock emissions (Van Middelaar et al., 2014). Opio et al., (2013) estimated that GHGs per unit of milk (kg CO_2e/kg fat and protein corrected milk) were much lower in Eastern and Western Europe, Russia, North America and Oceania (range 1.5–1.9) than in Sub-Saharan Africa (9.0) and Near East and North Africa (4.3). Methane is a major GHG in dairy farming and varies by location in dairying countries such as NZ, where it is lower in herds with higher-producing cows (Ledgard et al., 2020). Methane accounts for 10% of all GHGs in the USA, and of that, enteric fermentation from all ruminants accounts for 28% and stored manure for 10% (Retrieved on 2 September 2020, from https://www.epa.gov/ghgemissions/overview-greenhouse-gases). Novel additives, such as the algae, *Asparagopsis taxiformis,* show promise as a safe and effective feed additive for reducing CH_4 in ruminants (Roque et al., 2019). Emissions of N_2O arise during microbial denitrification of NO_3^- to nitrogen gas. Dairy sources of N_2O include long-term manure storage and volatilization of fertilizer, manure and urine applied to or deposited on crop land or pastures (Chadwick et al., 2018).

Different GHGs do not have directly comparable contributions to climate change, and therefore are scaled as CO_2e. The 100-year Global Warming Potential (**GWP100**), as denoted in both the Kyoto Protocol and Paris Agreement, set standard values for these relative contributions. The GWP100 inappropriately treats CH_4 the same as CO_2, despite CH_4 degrading rapidly in the atmosphere leading to an atmospheric lifetime of approximately 12 years. New metrics like GWP* (Lynch et al., 2020) account for gas lifespan, more accurately relating emissions to warming. With GWP* as the metric, modest

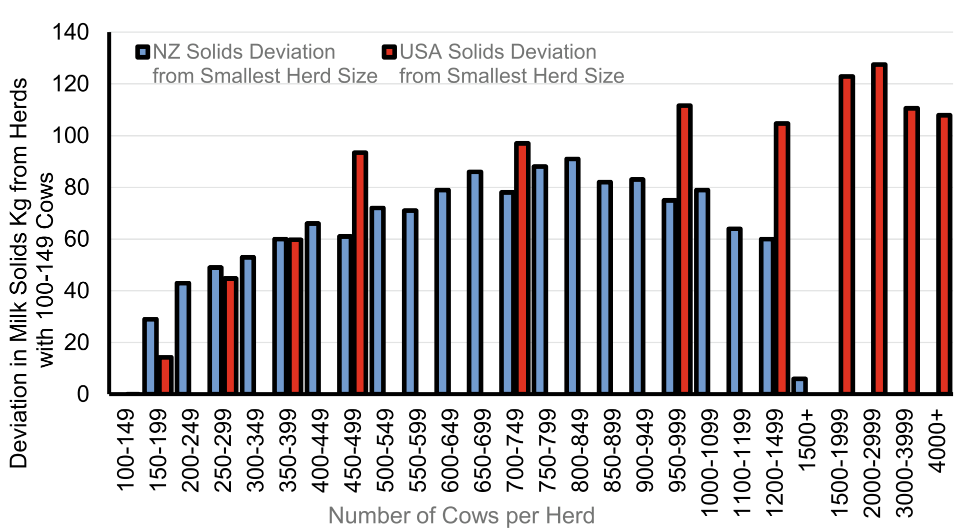

Fig. 4. Deviation in milk solids yield per cow per year from smallest herds (<150 cows) in NZ and US. Herd size groupings differed among official databases; therefore, values are reported at the highest end of their common range. Milk solids yield per cow for herds with 100–149 cows was 319 kg in NZ and 703 kg in USA.

mitigations of CH_4 (i.e., 0.3% annual decline) leads to a net-zero warming effect.

As an example, manure management plans supplemented by California state funds reduced methane from manure by 25% between 2015 and 2019 (Retrieved on 2 September 2020, from http://www.caclimateinvestments.ca.gov/press-releases/2019/9/19/california-department-of-food-and-agriculture-awards-nearly-102-million-for-dairy-methane-reduction-projects.)

Air quality

Dairy production can lead to emissions of NH_3, particulate matter (**PM**), and volatile organic compounds (**VOCs**). Ammonia contributes to water eutrophication, soil acidification and aerosol/particulate formation. Ammonia mitigation involves precise control of nitrogen intake to maximize animal N retention, precise control of nitrogen fertilization of cropland and timely management of manure. Environmental PM includes organic compounds, metals, dust, pollen, and mold (Retrieved on 2 September 2020, from https://www.epa.gov/pm-pollution/particulate-matter-pm-basics). Dairy specific PM is high in bacterial residues (e.g., endotoxin), which can elicit an immune response when inhaled. Workers might be vulnerable to chronic exposure (Davidson et al., 2018). Mitigation includes adding sprinklers to dry dirt pens which can reduce particulates by more than 50% (Cassel et al., 2003). Adding tall perennial vegetation around dairy facilities can trap airborne contaminants. Dairies may emit VOCs, predominantly from silage and feed handling, which contribute to ozone formation (Howard et al., 2010). Mitigation involves applying effective coverings on silage, ensiling with additives like potassium sorbate, and proper defacing of the silage pile (Mitloehner and Cohen, 2017).

Manure management and water pollution

Applying manure to land either through grazing or application becomes unsustainable if it overwhelms capacity of local ecosystems. Anaerobic digestion of manure produces CH_4 which can be used on-site or be distributed for energy or transportation fuel. Long-term liquid manure storage produces more CH_4 than fresh waste (Place and Mitloehner, 2010). Manure also contains inorganic N, which leads to emissions of N_2O or infiltration of NO_3^- after deposition or application (Chaddwick et al., 2011). N_2O emissions can be mitigated by controlling slurry DM content through decreasing amount of water utilized to flush manure. The best strategy to reduce N losses into the ecosystem is to reduce excess protein consumed by lactating cows.

Wastewater is an agricultural pollutant if nutrient rich water from manure lagoons and/or runoff enters local ecosystems (Fyfe et al., 2016). With high effluent rates, NO_3^- infiltration of surface and subsurface water can become a challenge. More than one-third of domestic wells exceeded the NO_3^-maximum contamination level in some areas of California that have high dairy activity. Dairy effluent may contain salts (e.g., alkaline and acid detergents, disinfectants, milk residues, trace quantities of veterinary chemicals) that can infiltrate subsurface water. Wastewater should be collected, and organic matter recovered before the water is used for irrigation (Taylor et al., 2016).

A new system converting manure and wastewater into clean water, sterile solids, and organic nitrogen fertilizers has been installed recently on dairy farms in the US (Retrieved on10 November 2020 https://www.sedron.com/varcor/). This system evolved from systems developed for villages in underdeveloped countries that did not have municipal water and sewage infrastructures.

Genetics of high-producing cows and herds

Genetic potential of dairy cattle in countries with modern dairying systems has accelerated rapidly (Weigel et al., 2017). From 1960 to 2017 average breeding values for milk yield of Holstein bulls in the US increased 75 kg/year (Retrieved on 6 August 2020 https://queries.uscdcb.com/eval/summary/trend.cfm). Milk solids produced by mature Holstein cows born in 2017 was 87% greater than cows born in 1970. Can this growth in yield continue? Cole et al. (2009) calculated breeding values if best chromosome segments across the Holstein breed were combined into a single cow. They concluded milk yield could increase by as much as 35 000 kg per 305-day lactation. Fitness traits declined when selection emphasis was primarily on yield, but today, selection for reproductive fitness, herd life, and resistance to disease accounts for more weight in selection indexes than yields of milk, butterfat, and protein, leading to improvements in fitness. Future selection indexes may include the rumen microbiome, because it has a reasonable level of heritability and affects milk yield and emissions (Wallace et al., 2019). Consumer preferences have and will continue to influence genetic selection. For example, dairy cattle breeders are selecting for the A2 version of beta-casein because of perceived health benefits and market demand. We expect farmers will be paid more for milk with different genotypes for kappa-casein because of their impact on cheese yield.

Advanced genetic and reproductive technologies

Emerging embryo technologies provide advantages that could lead to sales of embryos surpassing sales of semen. Removing cells from embryos before freezing and identifying genetic markers can be used to generate genomic breeding values to select embryos with optimal pairing of alleles. If technology allows development of sperm and oocytes from embryonic stem cells, genetically elite embryos could become parents. This nascent population could be theoretically generations beyond the current population and beyond current computing capabilities. Current models assume individual gene effects are independent, but genes function within interactive networks, and it will take massive computing capacity to deal with interactions among millions of single nucleotide polymorphisms in genomic databases. Epigenetics focuses on chemical modifications at DNA-, transcriptional- or translational-levels that regulate interaction between genes and their environment, without changing the DNA sequence (Bach, 2018). For example, differences in epigenome exist between calves born to heifers or cows (González-Recio et al., 2012). Emerging embryo technologies can influence how much protein a specific animal can make from a specific gene; therefore, a bovine embryo could be treated in culture or a recipient's nutrition altered after transfer to influence epigenetic development of the fetus (Crouse et al., 2019; Li, et al., 2020).

Fitting dairy cows to management and ecological niches

Thomet et al. (2011) observed that sustainable milk production was tightly linked to a cow's ability to convert forage into milk. As an example, the KiwiCross® breed derived from crossing Holstein-Friesian and Jersey cows in New Zealand improved productivity, fertility and longevity in their intensive grazing system (Retrieved 10 November 2020 from https://www.lic.co.nz/products-and-services/artificial-breeding/premier-sires/). To develop genetic selection programs, it is necessary to have well-developed pedigree, genotype, and performance databases. Today all large data sources exist in developed countries with intensive production and temperate climates. Increasing production from cattle in other systems requires development of regional- or climatic-specific genetic resources. Crossing of elite genetic merit bulls from developed countries with native cattle has improved productivity and sustainably in tropical countries (Bunning et al., 2019).

Sustainable feeding of high-performing cows and herds

Feed accounts for greatest cost of producing milk, and carefully managing intake of energy, protein, vitamins, and minerals should meet a cow's requirements without excretion of excess nutrients. This is extremely challenging with intensive grazing in temperament climates (Wilkinson et al., 2020), especially in countries such as Ireland and New Zealand that utilize mixtures of perennial rye grass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) in pastures (Department of Agriculture Food and Marine, 2018). This forage combination provides excess nitrogen intake relative to energy during the entire grazing season, and 60% of consumed nitrogen is excreted in urine, leading to nitrate toxicity in soils and subsoil water (Bryant et al., 2020). Supplementation of grazing cows with energy from stored feeds leads to underutilization of grass and lowers milk yield per hectare (Pinxterhuis et al., 2015), making intensive grazing less profitable (Bryant et al., 2020). Yields per cow are greater for cows fed a total mixed ration than those fed by intensive grazing for long seasons (Fig. 2); however, profitability per cow may be similar (White et al., 2002).

Lowering NDF and increasing starch within normal limits will increase milk protein and lower milk fat (Broderick, 2003), but markets globally differ in utilization of fat and protein, so farmers will produce what is most profitable in their market. Protein requirements in the cow are expressed as grams of available amino acids provided to the mammary gland. Rumen microbial amino acids comprise 50–60% and rumen-undegraded protein contributes 40–50% of required amino acids. Methionine and lysine are first limiting amino acids and their rumen-protected forms can be fed to meet requirements. Milk fat precursors include acetate and butyrate from rumen fermentation, and fatty acids from feeds and mobilized body fat. Dietary fatty acids are provided from feeds, commercial dry fatty acids (i.e., palmitic, oleic and stearic fatty acids), and commercial rumen-protected polyunsaturated fatty acids (such as linoleic and linolenic fatty acids).

Formulating balanced rations for high-producing cows

Ration balancing software uses rumen-based models to estimate nutrient levels provided by feed ingredients. Table 2 illustrates primary nutritional goals for Holstein cows at different stages of the dry period and lactation. Local pastures and harvested forages provide most economical feeds, but it may be essential to supplement cows with feeds such as maize or small grains or their silages (Pinxterhuis et al., 2015). Total mixed rations are common for feeding high-performing cows (Schingoethe, 2017) and these vary depending on available feeds and nutrient requirements (Table 2; Hutjens, 2018). Cows milked by robots may be fed a partial mixed ration or pasture to complement concentrate fed in the robot. Feed efficiency (**FE**) evaluates relationships between milk yield and feed inputs and includes measures such as kg of energy- or fat-corrected milk produced per kg of DM consumed. Determining FE requires measuring exact amount of feed consumed, knowing exact number cows, and knowing amount and composition of milk produced. Feed efficiency in grazing herds utilizes the same principle but may be expressed per hectare rather than per cow.

Feeding replacement heifers to gain more weight before weaning at 7–9 weeks of age stimulates development of more mammary stem cells, and this is linked to higher production during first lactation, Heifers should reach approximately 60% of adult weight by onset of puberty and should calve first at 22–24 months of age (Kertz et al., 2017).

Heat stress will increase as global temperatures increase. Substituting grain for some forages improves rate of feed passage and generates less heat from rumen fermentation, but sufficient high-quality forage is essential to maintain rumen health. Feeds that are optimal under heat stress should have greater NDF Digestibility and lower NDF than grass or legume forages. Replacing some carbohydrate-based energy with lipids reduces heat of fermentation in the rumen.

Reproductive management for the dairy cow and herd

Adoption of multiple reproductive technologies has provided primary means for accelerating genetic progress in dairy cattle (Fig. 5). Improved fertility in dairy cows is driving a shift to produce more beef from dairy-breed dams by inseminating dairy cows with semen from beef sires. Dairy-beef indexes for AI sires that are optimum matches for dairy cows are available (Berry and Ring, 2020). In modern dairy countries, farmers are using gender-sorted semen to inseminate their best phenotypic cows and their top genetic heifers to produce herd replacements. Broad use of multiple ovulation and embryo transfer is being replaced by *in vitro* maturation of oocytes, *in vitro* fertilization and *in vitro* culture of embryos, to exploit genetic merit of superior heifers and cows in the way AI extends use of superior sires. In Europe, number of transferable embryos per cow and per *in vitro* production session in dairy breeds increased from 1.6 in 2014 to 2.5 in 2018.

Fixed-time artificial insemination and pregnancy diagnosis

Programs to achieve fixed-time inseminations emerged in the 1990s, particularly in North and South America. These programs utilize GnRH, PGF2α and progesterone in various sequences to stimulate follicle waves, initiate luteolysis and induce precise time of ovulation. It has become clear that synchronizing follicle growth must be coupled precisely with induced regression of the corpus luteum to synchronize ovulation in a group of cows or heifers, so all animals in a group can be inseminated at a specific time. These systems have led to improvements in percentage of cows or heifers that become pregnant within any 21-day period of time, and "21-

Table 2
Expected yields and recommended intakes and concentrations of nutrient sources for Total Mixed Rations (TMR) for various lactation groups for Holstein cows producing approximately 12 000 kg annually. Values should be adjusted accordingly for other levels of production or for other breeds.

	Dry period		Early	Remaining lactation		
	Far off (−60 to −22 d)	Close-up (−21 to 0 d)	Postpartum (0–21 d)	Early (22–80 d)	Middle (81 to 200 d)	Late (>200 d)
Milk yield, kg/day	0	0	35	55	35	25
DM intake, kg/day	14	10	15	30	24	20
CP, g/kg	99	124	195	167	152	141
Rumen undegradable protein, g/kg	22	28	90	69	55	46
Metabolizable protein, g/kg	60	80	138	116	102	92
Net energy lactation, MJ/kg of DM	5.52	5.98	6.44	6.73	6.15	5.69
Ether extract, g/kg	20	30	40	50	50	30
ADF, g/kg	300	250	210	180	210	240
NDF, g/kg	400	350	300	280	300	320
Starch, g/kg	140	170	200	260	220	190

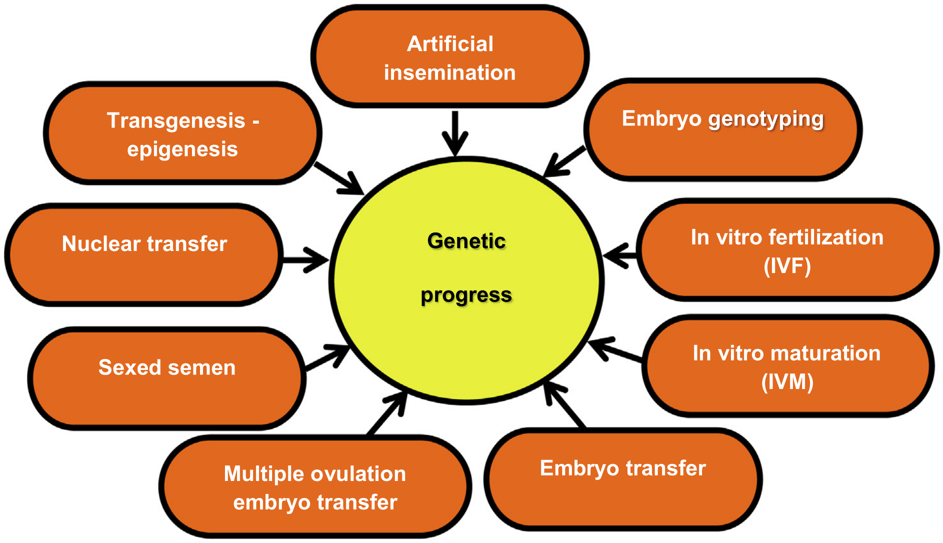

Fig. 5. Examples of common and emerging reproductive technologies that serve as vehicles for genetic progress in dairy cattle.

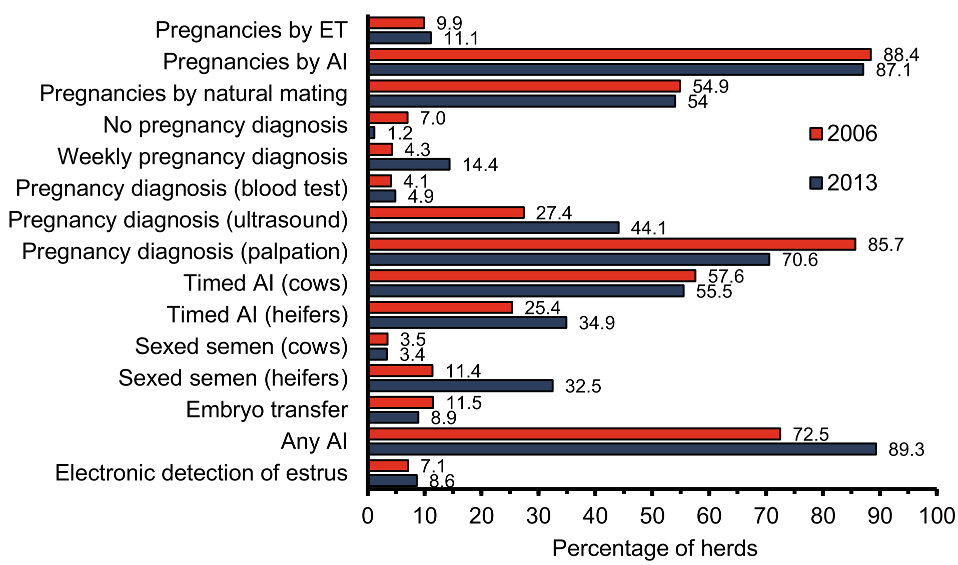

Fig. 6. Adoptive application of on-farm uses of reproductive technologies in 2006 and 2013 in the USA dairy herds (USDA, 2018). Abbreviations: ET = Embryo Transfer; AI = Artificial Insemination.

day Conception Rate" has become a common way of measuring reproductive performance in countries that utilize such systems. Increased use of transrectal ultrasonography for pregnancy diagnosis allows earlier reinsemination of non-pregnant cows (Fig. 6), and these exams are important to detect uterine or ovarian abnormalities, twin pregnancies, and estimation of conception dates from unobserved matings. Pregnancy-specific proteins are used to diagnose pregnancy by testing blood or milk samples collected 28–32 days after AI. For use with timed AI, blood or milk can be collected when a resynchronization program is initiated so the program can be continued if a cow is diagnosed not pregnant to the original AI.

Health of high-performing cows and herds

Health of dairy cattle is associated positively with milk yield and profitability. Infectious diseases such as Brucellosis, bovine tuberculosis and foot-and-mouth disease have been brought under control in advanced dairy regions, significantly because of government programs. Vaccines to prevent diseases such as bovine rhinotracheitis and bovine viral diarrhea have been adopted widely. Today's focus on health and wellness is toward prevention of metabolic health problems by improving nutrition and husbandry directed toward transition cows (LeBlanc et al., 2006), and farmworkers increasingly use sensor data to monitor transition health and detect diseases (Cabrera et al., 2020). Control of infectious and subclinical disease is aided by greater adoption of biosecurity (Hoe and Ruegg, 2006).

Mastitis remains a challenge because causative organisms are found in infected cows and a herd's environment. Mastitis is classified as subclinical (SCC > 200 000 cells/mL) or clinical (abnormal milk with or without abnormal mammary gland appearance). Subclinical mastitis is increasingly well-controlled, but incidence of clinical mastitis has increased (Fig. 7; Ruegg, 2017a and 2017b).

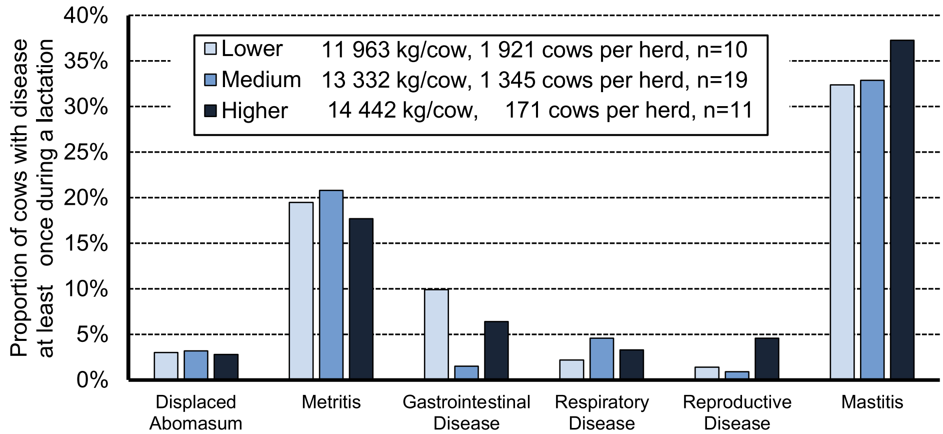

Fig. 7. Incidence of diseases occurring at least once during one lactation in 40 large dairy herds in Wisconsin classified by different milk yields. There was no statistical difference among yield groups for any of the diseases.

Table 3
Selected performance data for dairy cattle herds with different milk yield levels in the Upper Midwest of the USA.[1]

Traits	Milk yield category (kg/cow per year)				
	<7 711	7 712–9 525	9 526–10 234	10 235–13 608	>13 608
Herds, *n*	160	327	651	645	113
Milk, kg/cow per year	6 416	8 734	10 471	12 332	14 338
Peak milk parity 3+, kg/day	32	40	48	55	62
Cows SCC < 100 000 cells, %	53	61	67	74	78
Cows SCC > 200 000 cells, %	29.8	23.4	19.2	14.7	12.3
Bulk tank SCC, cells	345 000	267 000	212 000	165 000	141 000
Cows culled < 60 DIM, %	7.6	7.2	7.6	8.0	7.5
Milk cow death rate, %	6.9	5.8	5.8	5.6	5.1
Milk cows died or culled, %	39.7	42.3	44.2	43.4	41.7

Abbreviations: SCC = somatic cell count, DIM = days in milk.
[1] Retrieved on 2 September 2020, from https://dairy.agsource.com/industry-benchmarks/.

Concerns about antimicrobial resistance have led some countries to reduce usage of antimicrobials in food animals (Ruegg, 2017b). Antimicrobial dry cow therapy accounts for most antimicrobials used on dairy farms, but herds can reduce mastitis using non-antibiotic therapies and genomic selection.

There is little change in incidence of disease as milk yield increases, as illustrated by data from 40 herds producing at different levels (Fig. 7); these herds had an average SCC of 142 550, a cow mortality rate of 5.5%, and an overall cow turnover rate of 37.8%. Performance benchmarks for 1 896 dairy herds in the upper Midwest of the USA were summarized for January 2020 (Table 3). Cows in herds with greatest annual yield per cow produced 2.2-times more milk and had 40% fewer cows with subclinical mastitis than herds with smallest yields. Higher-producing herds had about half as many cows that exhibited subclinical mastitis in early lactation or experienced new intramammary infections.

Transitional diseases and negative energy balance

Metabolic diseases during the peripartum transition period, including hypocalcemia, ketosis, and displaced abomasum, increase risk of other conditions such as metritis and lameness. Postpartum uterine diseases, including retained fetal membranes, metritis, endometritis, and subclinical endometritis occur in about 40% of cows (Sheldon et al., 2020). Negative energy balance and uterine disease are linked: the odds of metritis increased almost 3-fold for every kg reduction in DM intake in the week before calving, and metritis increased 3.4-fold for postpartum dairy cows with $\geq$1.2 mmol/L beta-hydroxybutyrate in peripheral blood the week following calving. Negative energy balance impairs neutrophil function and metritis causes visceral pain and reduces appetite, which increases negative energy balance (Stojkov et al., 2015). Postpartum uterine diseases not only affects the uterus but also perturbs ovarian function (Sheldon et al., 2020). Limiting negative energy balance in high-producing dairy cows is the first step in supporting both reproductive health and animal well-being.

It is not inevitable that dairy cows with a high milk yield exhibit negative energy balance. Up to half of high-performing cows maintain or increase body condition score or weight during the first three weeks postpartum (Carvalho et al., 2014). Among high-producing Holstein cows, about 20% gain body condition or weight during 3 weeks after calving and about 30% maintain body condition immediately post-calving. Greater genetic selection against negative energy balance during the first 3 weeks postpartum could eliminate many postpartum disease problems.

Resilient dairy cows prevent disease by avoiding, tolerating and resisting pathogenic bacteria (Sheldon et al., 2020). Avoiding postpartum uterine infection is particularly difficult when high-producing dairy cows are kept closely confined; therefore, stocking rate in early postpartum cow pens should be kept at about 80% of capacity relative to pens beyond the transition period. Farmers can reduce uterine disease by maintaining hygiene, monitoring calving cows, and selecting for calving ease.

For many years, a strategy of 'one calving per cow per year' has prevailed, especially in seasonal grazing herds. In herds that are fed stored feeds, it could be beneficial to prolong 2nd and later lactations through genetic selection, milking 3-times or more a day and increasing energy intake to reduce peri-parturient problems as well as non-productive dry periods per life-time. This could benefit animal welfare and improve profitability (Dobson et al., 2007). Uterine disease could be avoided by inducing lactation in cows not needed to produce replacements. Lactation was induced successfully in 1 500 barren Holstein dairy cows in northern Mexico using hormones that mimic natural hormonal changes during pregnancy (Mellado et al., 2011). Among cows induced to lactate after one natural lactation, milk yield averaged 7 607 kg and this increased to 9 548 kg for cows that had six previous natural lactations.

Dairy cows and farming in the future

High performance cows and herds begin with cows having genes that are adapted for their environments, with balanced emphasis on fitness and yield of milk components. Application of genomic selection will result in new breeds or new versions of existing breeds that will fit dairy farming niches globally, and this will increase output per cow and lower environmental impacts. Genetic traits will be transferred among and between regions through embryos and for some single genes by gene editing. Dairying in the northern hemisphere will shift northward across country borders because of global warming and changes in availability of water. Understanding of dairy cow nutrition will continue to evolve with a continued focus on the transition period, but there will also be increased emphasis on feed efficiency and on reducing variation in body condition scores. There will be significant nutritional fine-tuning in lowering nutrients excreted in urine and feces, particularly where nitrogen excretion is degrading ground water. Health of dairy cows will be improved significantly through greater genetic emphasis to decrease clinical mastitis, lameness and metabolic diseases. Use of antimicrobial drugs in dairy cattle will be reduced drastically or eliminated and replaced with biologics or with externally applied procedures that do not utilize drugs. Dairy farms will continue to lower environmental impacts by adopting systems that convert manure and wastewater into potable water, bioenergy and nitrogen fertilizers – such systems will be affordable for larger farms or through shared use by smaller farms. Milk's health benefits will be enhanced through increases in qualities of milk proteins and fats. Through sustainable intensification, the dairy industry can produce milk needed for our future global population.

Ethics statement

No experimental procedures with animals nor human subjects were conducted by the authors for this paper.

Data and model availability statement

Various sources of data were downloaded from public sources to produce some of the illustrations created by the authors. Sources of these data are cited in descriptions of Tables and Figures. Data were not deposited in a specific repository but are available from the corresponding author.

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Declaration of interest

No potential conflict of interest is reported by the authors.

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