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Chapter 8
Research and Innovation
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Research
Report

8. Research and innovation

Research and innovation has helped the livestock sector in Canada to find the optimal use of scarce resources, all while combatting animal disease and responding to the rising global demand for protein. This section outlines some of the ways that livestock R&D has advanced in North America in terms of production and yield of animal products, as well as improved animal welfare and environmental sustainability.

8.1 Challenges in Animal Agriculture Confronting Innovation

The livestock industry in Canada has made substantial progress over the past two decades in responding to the challenges it faces on all fronts from the environment, from human and animal health and welfare concerns, on the trade and consumer demand front and from society as a whole. We present here the Dublin Declaration as a summary of the challenges for livestock and the importance of meeting these challenges through research and innovation.

8.1.1 The Dublin Declaration of Scientists and the Societal Role of Livestock

The Dublin Declaration (2023) was the result of an agreement that was made at the International Summit on the Societal Role of Meat in Dublin, Ireland in the fall of 2022. The goal of this initiative was to provide the latest evidence and developments in knowledge around the societal role of meat. As of September 25, 2023, 1,145 persons have signed the Dublin Declaration (The Dublin Declaration, 2023), with the purpose of giving a voice to scientists around the world who do research in various disciplines to improve and innovate for the future of animal agriculture. Findings from the symposium have been published in the April 2023 volume of the journal *Animal Frontiers*, providing up-to-date evidence on meat as it relates to human nutrition and health, culture, socio-economic factors, the environment, and ethics.

The Dublin Declaration focused its objectives around five themes in an effort to prioritize the research around five issues:

Challenges for livestock. This theme focuses on the dual challenge for livestock: to increase supply in response to rising global demand for animal-sourced foods that address nutritional gaps, while doing so within the constraints of climate change, biodiversity, nutrient flows, and animal health and welfare to secure livestock-dependent livelihoods and address sustainability challenges through evidence-based solutions.

Livestock and human health. This theme draws out the critical dietary and health role for livestock products, to counter some of the negative press around its link to cardio-vascular diseases and cancer, drawing on bio-evolutionary, anthropological, physiological, and epidemiological research that underscores the importance of regular consumption of meat, dairy, and eggs as part of a well-balanced diet that is advantageous for human beings.

Livestock and the environment. This theme researches the benefits of farmed and herded animals for maintaining a circular flow of materials in agriculture, through the recycling of inedible biomass generated as by-products of plant-based foods in the human diet. Livestock also play a role valorising marginal lands not suitable for growing crops for human consumption. It is also important for generating environmental benefits, including biodiversity, carbon sequestration, improved soil health, and watershed protection as important ecosystem services. There is no doubt that more research and action is needed to reduce climate change impacts of livestock production. It is also important to communicate those findings effectively to a broader audience. This is to inform one-size-fits-all agendas which are currently calling for drastic reductions in livestock numbers and more serious environmental problems globally.

Livestock and socioeconomics. This theme addresses the historical and future role of livestock for providing food, clothing, power, manure, employment, and income as well as assets, collateral insurance, and social status to millions around the world in both developed and developing countries. In some communities, livestock is one of the few assets women can own as an entry point to gender equality, family and community welfare, and food security. Livestock is a long-proven method to create healthy nutrition and secure livelihoods deeply embedded in cultural values everywhere.

Outlook for livestock. This final theme argues that livestock will continue to provide solutions for remaining a critical bedrock of societies for staying within the Earth's safe operating zone of planetary boundaries well into the future.

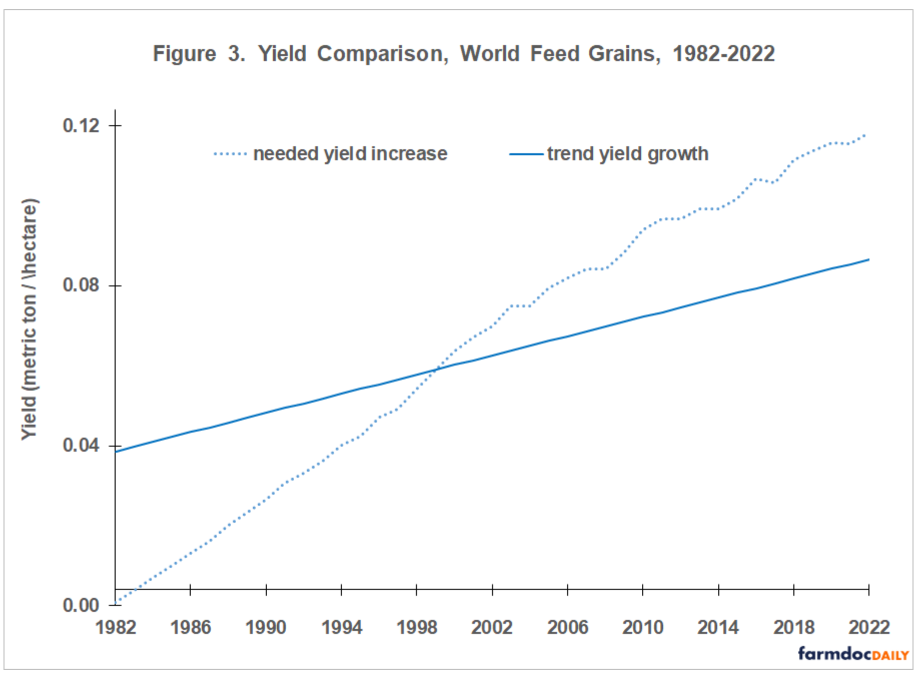
8.1.2 Efficiency and Sustainability in Resource Use

In the introduction of his 2002 article, Vaclav Smil remarked that "Von Liebig noted in his most famous book [published in 1840] that agriculture's principal objective is the production of digestible N" (Smil, 2002, p. 126). Digestible nitrogen would be referred to today as protein or amino acids. Under this conception of agriculture, field crops and horticulture are somewhat limited with key gaps in the supply of amino acids; animal agriculture is the element that converts feedstuffs from products either inedible for humans or low/deficient in protein/amino acids, to animal products higher or more complete in protein/amino acids. The efficiency of conversion – from the land base to feedstuffs, and from feedstuffs to animal proteins – is of paramount importance.

This is especially important because efficiency in animal conversion of feedstuffs interfaces with crop feedstuff yields. In this regard, Zulauf (2022) analyzed the problem of global yield drag: the proportion of growth feedstuff demand that cannot be satisfied by crop yield growth, and must instead be met by introducing new land into production. Figure 8.1 below, reprinted from Zulauf, shows that, starting from the early 1980's, for global feed grains (corn, barley, oats, and sorghum), yield growth in these crops was only able to keep up with demand up until 2000; since then, additional land has been needed to supplement yield growth in order to provide the production to meet demand.

Feed grains are intermediate products, primarily supplying animal agriculture as an end use. As such, efficiency in animal conversion of these feedstuffs has a direct effect on demand for feedstuffs, and influences yield drag and the associated need to bring additional acreage into cultivation to meet animal protein demand.

Figure 8.1. Trend Yields, Actual Yields, and Yield Drag: Global Feed Grains*



*Feed grains are barley, corn, millet, oats, and sorghum.
Reprinted from: Zulauf, C. (2022). The World's Increasing Need for Cropped Land. Farmdoc Daily, 12(173). https://farmdocdaily.illinois.edu/2022/11/the-worlds-increasing-need-for-cropped-land.html.

8.1.3 Access and Expense of Workforce

A significant problem across agricultural segments is access and cost of labour, and animal agriculture is affected along with other segments. Technology and innovation has developed to substitute for labour on farms, and this remains an ongoing process driving innovation in animal agriculture. Examples include robotic milking, cameras, and other precision technologies (see section 8.3).

8.1.4 Extreme Weather and Climate Change

Animal agriculture is subject to the effects of extreme weather and climate change. This is the case in a variety of respects. There are at least three distinct aspects. Extreme weather and climate change can impact the nature and feasibility of feed crops that support animal agriculture. Changes in temperature and extreme weather events causing adverse situations such as flooding directly impact the growth and welfare of farm animals. Animal pathogens can fluctuate in response to climate change, and foreign animal diseases can become a greater threat as a result.

For example, a review Thornton *et al.* (2014) observed "Changes in climate variability and in the frequency of extreme [climate] events may have substantial impacts on the prevalence and distribution of pests, weeds, and crop and livestock diseases" (Thornton et al., 2014, p. 3319).

A recent study of vulnerability to climate change in Ontario drew from the scientific literature in arriving at the following illustration of the effect extreme weather on dairy cows:

> *Dairy cows are particularly sensitive to high air temperatures due to additional metabolic heat generated during lactation. Exposure to heat over 32°C results in heat stress causing impacts such as reduced feed intake, lower milk yields (12 kg/day per cow), and reproductive problems (e.g. 26% lower conception rate), impacting farm revenue and timing of operations such as calving… Additionally, heat stress compromises cows' immune systems, making them vulnerable to disease, while extreme levels of heat stress result in an increased likelihood of mortality (27% greater mortality rate compared to a period with no heat stress) … Carryover effects of stress are known to persist even after the heatwave ends" (Ontario Ministry of the Environment, Conservation and Parks, 2023, p. 114).*

Significant adverse effects were also observed for beef cattle, swine, and poultry, and each of dairy, beef, swine, and poultry were classed as high climate risk by 2050 (Ontario Ministry of the Environment, Conservation and Parks, 2023)

8.1.5 Disease Threats

Animal agriculture in Canada faces ongoing threat of disease, in multiple dimensions. Animal diseases cause morbidity or death of animals are a source of reduced growth, increased costs, decreased revenue, and decreased welfare for affected animals. Many of these are production limiting diseases that are left to the individual producer and veterinarian to bring under control, and can undermine the financial viability of producers affected. A subset of these diseases must be immediately notified to the Canadian Food Inspection Agency, as they "are diseases exotic to Canada for which there are no control or eradication programs"[1] and CFIA can undertake control measures.

[1] For a list of immediately notifiable diseases, see https://inspection.canada.ca/animal-health/terrestrial-animals/diseases/immediately-notifiable/eng/1305670991321/1305671848331.

Another subset are Reportable Animal Diseases under the federal Health of Animals Act and are reported internationally to the World Animal Health Organization[2]. For these diseases, CFIA immediately takes responsibility to bring the disease under control, and other countries can limit imports in response to the disease. As a result of the limitations on trade, it is not only the affected producer that is adversely impacted by the disease – whole industries can be greatly impacted.

With Canada's overwhelming exporting interest in pork and also in beef, the occurrence of a reportable disease could be disastrous on affected industries. Canada had this experience following the discovery of Bovine Spongiform Encephalopathy (BSE) in 2003. The key threats today are African Swine Fever (ASF-pork), and Foot and Mouth Disease (pork, beef, and dairy). African Swine Fever poses an especially ominous threat, exacerbated by the presence of wild pigs, not native to Canada, that present a vessel of infectious agent in the wild if ASF were to occur in Canada- making eradication of the disease much more difficult. Avian influenza also poses a major threat to poultry industries.

8.1.6 Environmental Sustainability

Productivity and efficiency in the output of animal products relative to the land base are essential for environmental sustainability. There are also specific aspects that are issues for animal agriculture and the target for research and innovation. Livestock are large components of agricultural greenhouse gases, especially methane. Livestock manure is an important source of nitrogen and phosphorus deposition, and can be a source of runoff and pollution of waterways. Livestock manure can also be associated with nitrogen leaching into ground water. Manure-borne pathogens, notably coliforms and *E. coli*, can also contaminate waterways and ground water.

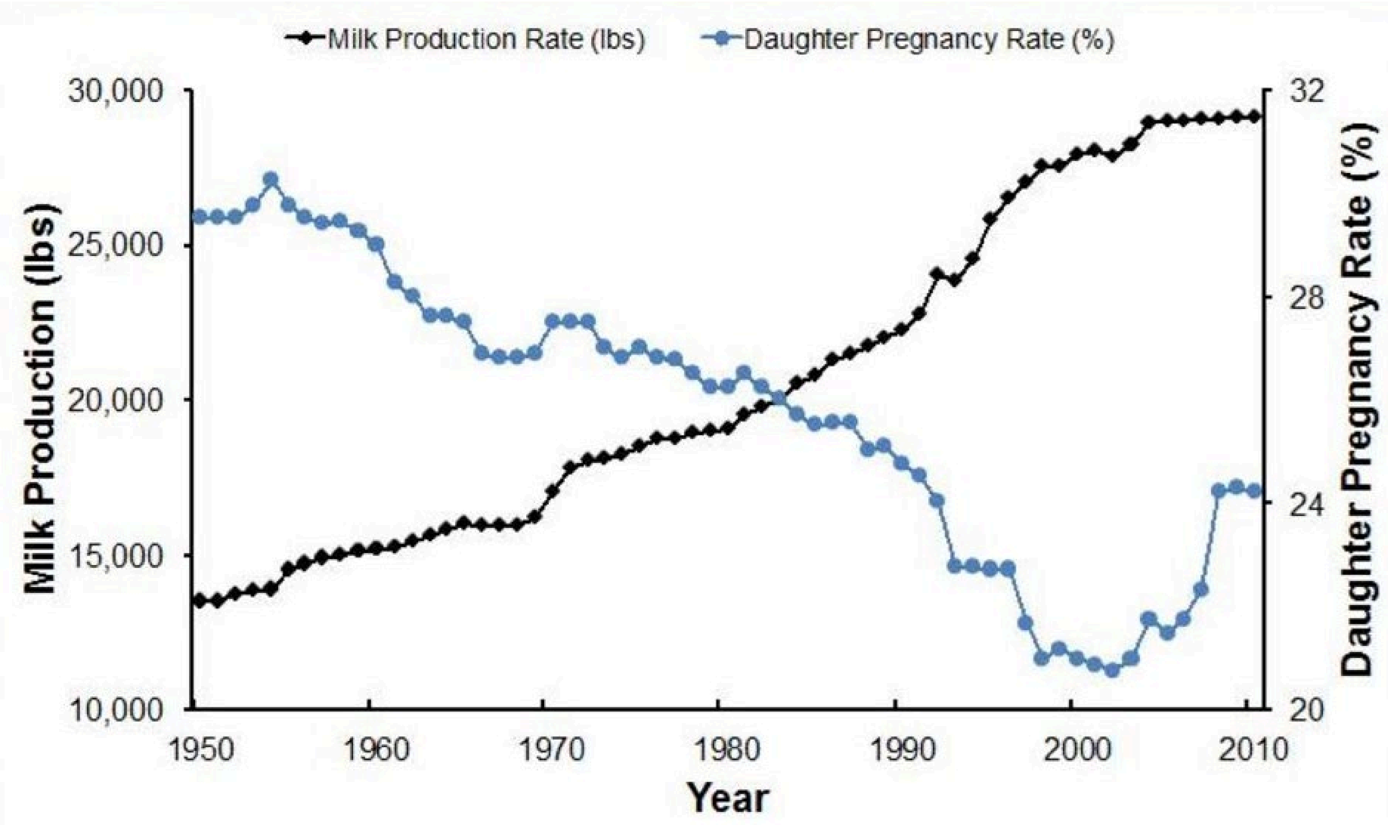
8.1.7 Animal Welfare

Grandin (2014) identified two types of animal welfare issues: "abuse or neglect of animals, caused by direct action by humans, and welfare issues where either a process or equipment has to be changed to improve animal welfare" (2014, p. 461). In the latter case, she specifically identified the problem of "biological system overload," defined as "concern that pushing the animal to produce more meat, eggs, or milk will cause both increasing welfare problems and a decline of functionality" (p. 466).

An illustration highlighted by Grandin and appearing in Spencer (2013) is provided below in Figure 8.2. The figure plots US milk production per cow vs daughter pregnancy rate, defined as the share of cows eligible to become pregnant in a 21-day period that actually become pregnant. The inference is that by focusing breeding traits related directly to milk production, US milk production per cow has increased impressively; however, this focus has come at the exclusion of reproductive rate, borne out in decreasing daughter pregnancy rate. Grandin provides other examples in poultry and swine. Grandin observes, "Both producers and scientists may think that we have to keep increasing production to feed a growing population. The author fears that an over emphasis on production may lower disease resistance. A new disease, Porcine Epidemic Diarrhea, is killing many piglets and the virus is very virulent and it can survive in manure and feed for seven to twenty-eight days. Dead piglets do not feed people" (p. 467).

[2] For a list of reportable diseases, see https://animalhealth.ca/disease-response/.

Figure 8.2 US Milk Production per Cow vs. Daughter Pregnancy Rate



Source: Reprinted from Spencer, T.E. (2013). Early pregnancy: Concepts, challenges, and potential solutions. *Animal Frontiers*, 3(4), 48–55.

8.1.8 Antimicrobial Resistance

Livestock are confronted by pathogens in their growth cycle which threaten to slow growth, cause morbidity and mortality, and compromise welfare. Both in anticipation of disease pathogen threats and in response to them, multiple refinements in nutrition, housing, ventilation, and both acute and therapeutic pharmaceutical treatments are deployed. Pharmaceutical treatments have met with stunning successes with regard to animal growth, health maintenance, prevented suffering, and decreased mortality. However, they are subject to other risks which must be addressed: the development of resistant pathogens within the target species, and pathogen resistance that spills over to impact other species, notably into human medicine.

With regard to the first issue, coccidiosis in poultry provides an illustration. Poultry are subject to infection by intestinal parasites that have significant negative impacts of their growth and health. The development of a modern commercial poultry industry in North America and around the world has been shaped in part by the constraint imposed by these diseases.

The development of treatments for intestinal parasites in poultry accelerated after the Second World War. One of the significant chemical products launched at this time was the sulphur-based feed additive sulphaquinoxaline in 1948, and many others followed (De Gussem, 2007). This included the “arsenical” group of medicated feed additives, such as roxarsone as both growth promotant and anti-coccidial, and nitarsone, a preventative treatment for blackhead in turkey.

The use of these products allowed the poultry industry to grow and expand more quickly (De Gussem, 2007). This is illustrated in Figure 8.3 for anti-coccidial treatments, from Reid (1990). US broiler production literally tripled between 1950 and 1970; this was coincident with a proliferation in available chemical treatments as medicated feed additives. It also allowed for a decrease in the consumer cost of chicken; Campbell (2008) notes that

“Following the commercial introduction of SQ [sulphaquinoxaline] in 1948, the price of broiler chickens in the United States declined sharply, and continued to decline over many years, during which sulphaquinoxaline was succeeded by other coccidiostats” (p. 941) (Figure 8.4).

However, the efforts to combat intestinal parasites has met with the problem of resistance. As a result, many of the chemical feed additive products introduced in the 1950’s, 60’s, and 70’s were withdrawn or declined in use due to resistance problems (De Gussem, 2007; Reid, 1990). As chemical feed additives declined in popularity due to pest resistance, these were replaced by a new category of control products: ionophores. The first ionophores were introduced in the early 1970’s (De Gussem, 2007); this can be identified as monensin in Figure 8.3. The period following the early 1970’s shown in Figure 8.3 is one in which broiler production again increased very rapidly. There are surely a number of reasons for this, including rapid increases in chicken demand, but it is consistent with the increased availability of ionophore anti-coccidials that were less prone to resistance than chemical additives (De Gussem, 2007). Today, ionophores are facing pressure as part of a broader concern regarding use of drugs in livestock production, which in turn drives the demand for alternative solutions to the issue of intestinal parasites in poultry.

Figure 8.3. Anticoccidial Products Introduced in the US vs. Broiler Chicken Production 1930-1990

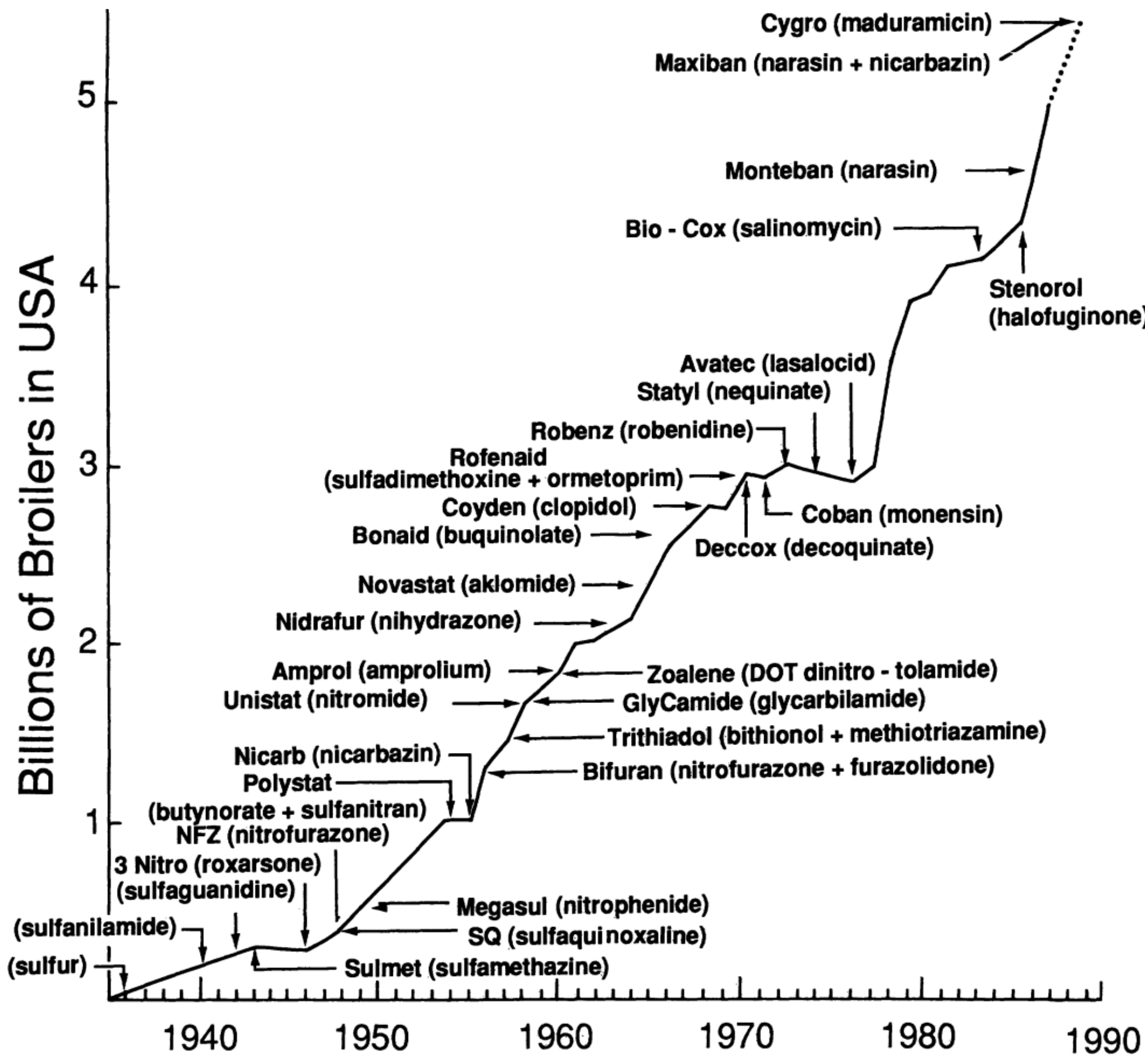


Fig. 1. Anticoccidial drugs introduced in the United States during 1936–89 plotted on USDA estimates of numbers of broilers produced. Registered trade names begin with a capital letter and generic names are shown in lower case.

Source: Reprinted from Reid, W. M. (1990). History of avian medicine in the United States. X. Control of coccidiosis. *Avian Diseases*, *34*(3), 509–525.

Figure 8.4. US Chicken Prices through time (2003 USD)

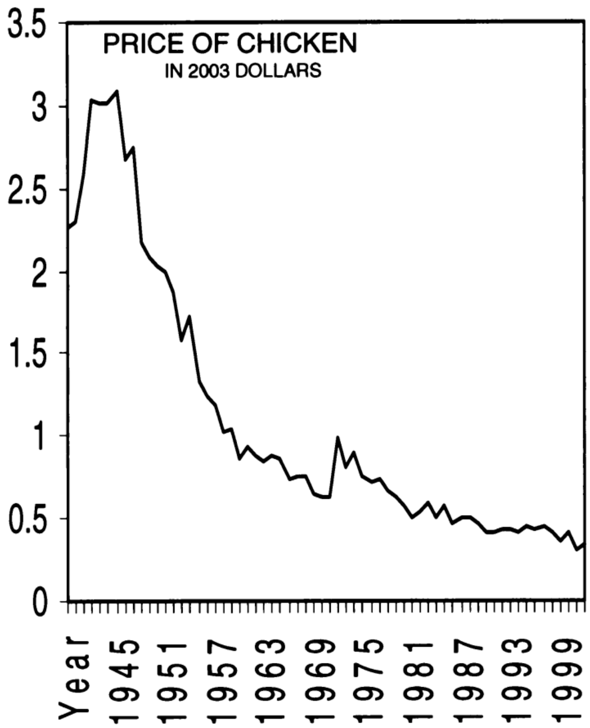


FIGURE 7. Decline in price of poultry meat following introduction of coccidiostats in 1948. Annual average of monthly live-weight price of chicken per pound received by farmers (expressed in 2003 dollars calculated from data of the Federal Reserve Bank of Minneapolis, Minnesota, 2006). The decline reflects an increase in the use of intensive production methods, which were made practicable by the introduction of the drugs. No attempt is made to disentangle the causative contributions of the methods and the drugs.

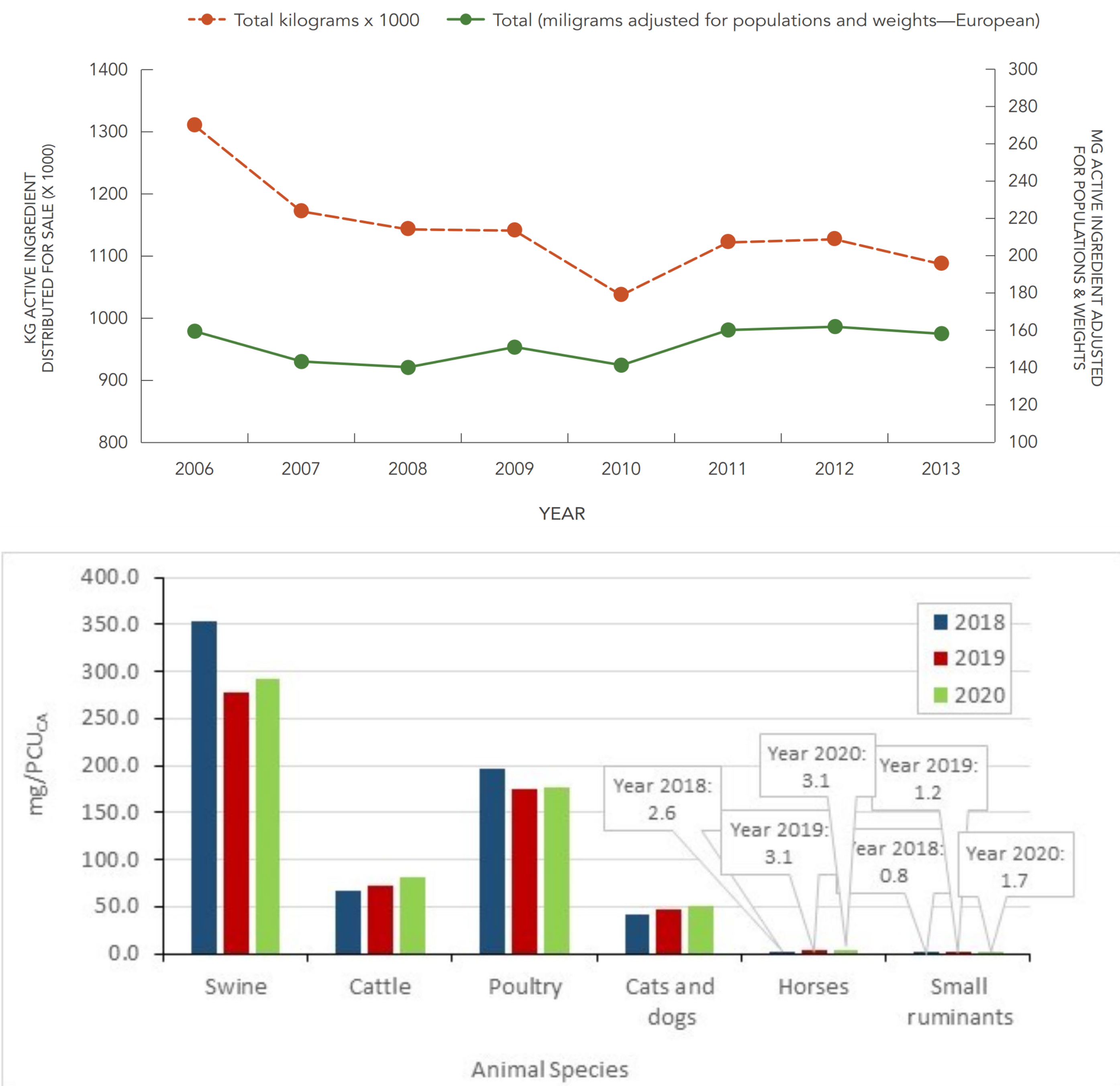
Source: Reprinted from Campbell, W. C. (2008). History of the discovery of sulfaquinoxaline as a coccidiostat. *Journal of Parasitology*, *94*(4), 934–945.

The decline in Figure 8.4 reflects an increase in the use of intensive production methods, which were made practicable by the introduction of the drugs. No attempt is made to disentangle the causative contributions of the methods and the drugs.

The second and related issue of risk is of antimicrobial resistance across species. This has been a matter of critical focus for innovation in animal industries, both in terms of data collection and monitoring, and judicious (and generally reduced) use of sub-therapeutic treatments. This is especially the case for medically important antimicrobial products. Figure 8.5. below presents data collected under the Canadian Integrated Program for Antimicrobial Resistance Surveillance (CIPARS). The data shows that, comparing 2006-2013 with 2018-2021, total use of medically important antimicrobials in animals has decreased. When this is adjusted for livestock populations and animal weights, usage of these antimicrobials has been steady at around 160 mg/PCUEU (Public Health Agency of Canada, 2015, 2022). The challenge has been to maintain satisfactory levels of animal health and welfare and decrease the use of antimicrobials, and thus minimize the contribution of animal medications to the broader problem of pathogen resistance in human medicine.

Figure 8.5. Medically-important antimicrobials (adjusted for population and weights, mg/PCUCA) by animal species, CIPARS, 2006-2013 and 2018-2020

FIGURE 4: Medically-important antimicrobials distributed for use in animals over time; measured as kg active ingredient and mg active ingredient, adjusted for population and weight[h]



Source: Canadian Antimicrobial Resistance Surveillance System Reports, 2015 and 2022.

8.2 Breaches and Erosion in Social Capital

Significant responsibility and public trust is devolved to the institutions of animal agriculture and to the producers/businesses engaged in animal production, handling, and processing. In effect, they are charged with maintaining the integrity of the public image of the product category, quite apart from their own production processes, marketing, and profitability. Gaps in this public trust are an important source of risk to animal industries, and a source of increased scrutiny. This is complicated by public perceptions and expectations of animal welfare and the food system that fluctuate over time.

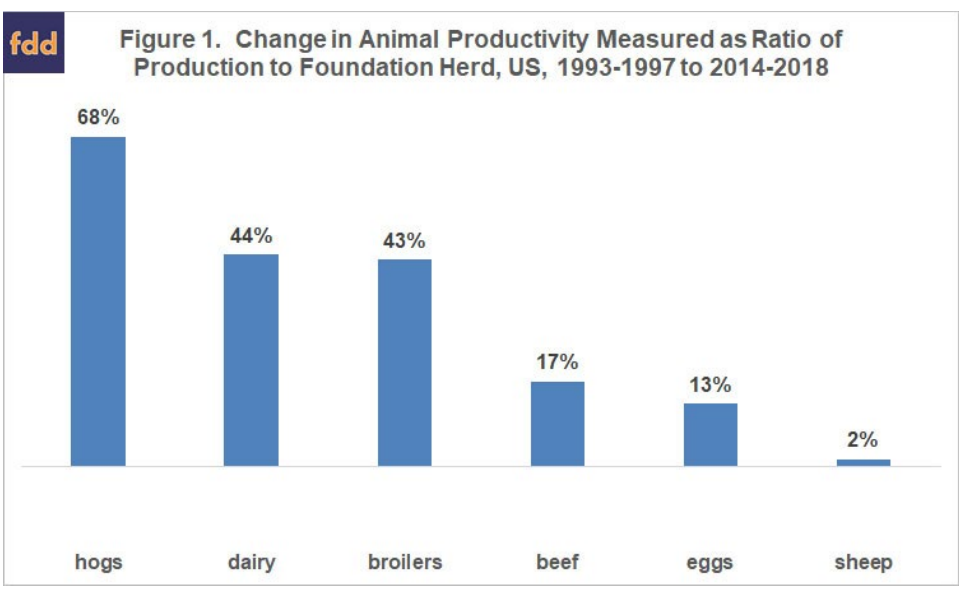
The most egregious example is animal activism seeking to discredit animal agriculture and carries the risk of swaying broader public opinion, amplified through the release of covert videos of incidences of animal abuse or suffering, and legal action taken against animal industries. The perception that animal facilities are excessively crowded; use processes viewed by some as wasteful, polluting, or inappropriate; or fail to treat its human resource stock fairly or safely are factors potentially undermining the legitimacy of animal agriculture institutions. This risks broader actions by governments and consumers against animal industries.

Trust can also erode from within animal agriculture. Changes in structure and interests can weaken institutions and make changes in collective standards more difficult to make. Conversely, if institutions are only seen as serving the interests of a subset, they can become frail.

8.3 Innovation and Progress in Animal Agriculture

Most indicators of efficiency progress and innovation in animal agriculture are compiled on a species-specific basis and deal with conversion efficiency, and are discussed elsewhere in this paper. Zulauf (2019) considers an alternative approach, in which efficiency is measured by taking animal production relative to the "foundation herd," and comparisons can be made across species. Essentially it views the breeding herd as the overhead that enables production of meat, milk, and eggs, and then indicates how the share of production relative to breeding animal overhead has changed over time. Zulauf (2019) compiles this measure for US animal agriculture and applies it in comparing the change from 1993-1997 (average) with 2014-18 (average) to measure progress. He finds that hogs had a 68% increase in productivity over the 20-year time period. Dairy and poultry (broilers) had approximately the same gains in productivity (44% and 43%). Beef had the lowest gain in productivity of the four, at an increase of 17% between the two time periods.

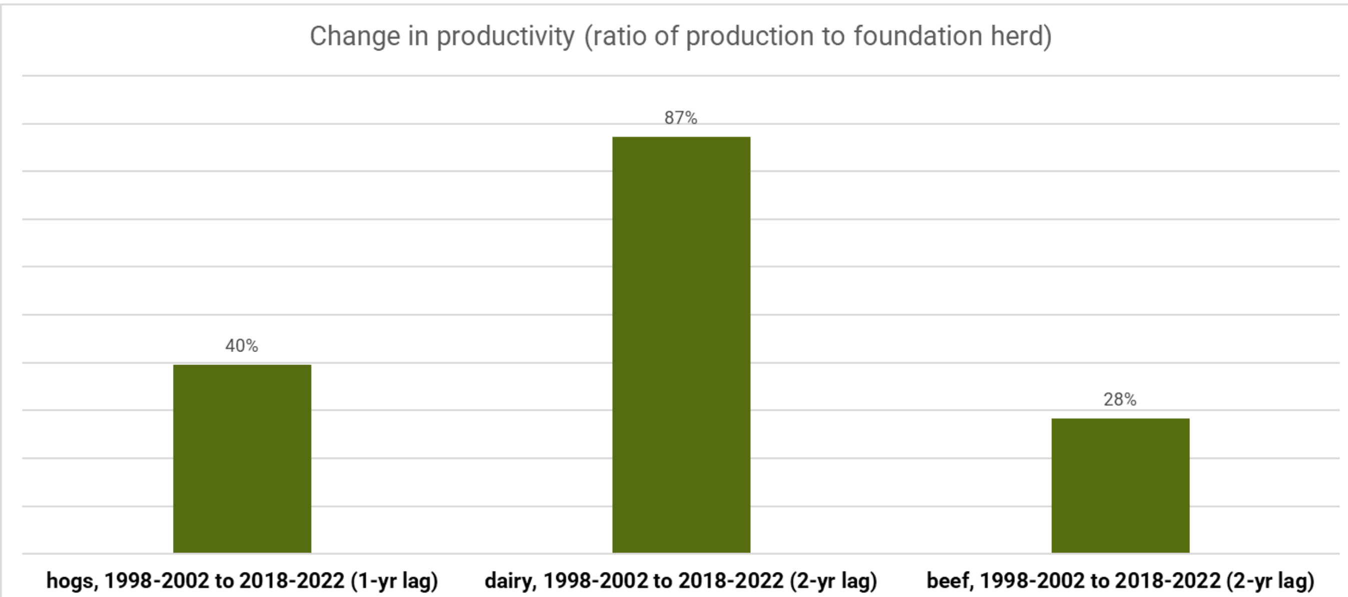
Figure 8.6. Change in animal productivity (ratio of production to foundation herd, USA).



Reprinted from Zulauf, C. (2019). Comparing Livestock Productivity Since 1993. *Farmdoc Daily*, *9*(96). https://farmdocdaily.illinois.edu/2019/05/comparing-livestock-productivity-since-1993.html

A similar analysis is undertaken for Canada here. Figure 8.7. compares hogs, dairy, and beef for the most recent five-year average available (2018-2022) for period 2, and approximately 20 years prior for period 1. In keeping with Zulauf, the foundation herd is lagged by two years for beef and dairy and one year for hogs. Like the results obtained in the US, output relative to the foundation herd has increased markedly in Canada over a relatively short period. The figure shows that in Canada, milk production increased the most relative to the foundation herd between the two periods (87%). In the case of broilers, historical data were not available on the broiler breeder population therefore broilers were left out of the Canadian analysis.

Figure 8.7. Productivity relative to foundation herds, Canada



Sources of data: Statistics Canada Tables 32-10-0126 (pig meat), 32-10-0160 (gilts and sows); 32-10-0130 (dairy cows and beef cows), 32-10-0053 (food supply, beef); Statistics Canada Hog Statistics reports, 1997-2001 (sows and bred gilts); Canadian Dairy Commission (milk production).

Figure 8.8 provides a snapshot of livestock productivity through the decades. In the seventies, the average broiler weight at 56 days old was 1.8kg; by 2005, it had more than doubled to 4.2kg per broiler. Feed efficiency in beef has improved over time: in 1950, it required 10 pounds of feed to produce one pound of beef; in 2010, this was down to 6 pounds of feed. Milk productivity in Canada has more than tripled in 50 years: in 1961, the average dairy cow produced 2,787kg milk per year; in 2021, it was 9,647 kg/cow/year (see Figure 10.4 for international comparisons of milk productivity through time).

Figure 8.8. Livestock productivity, then and now

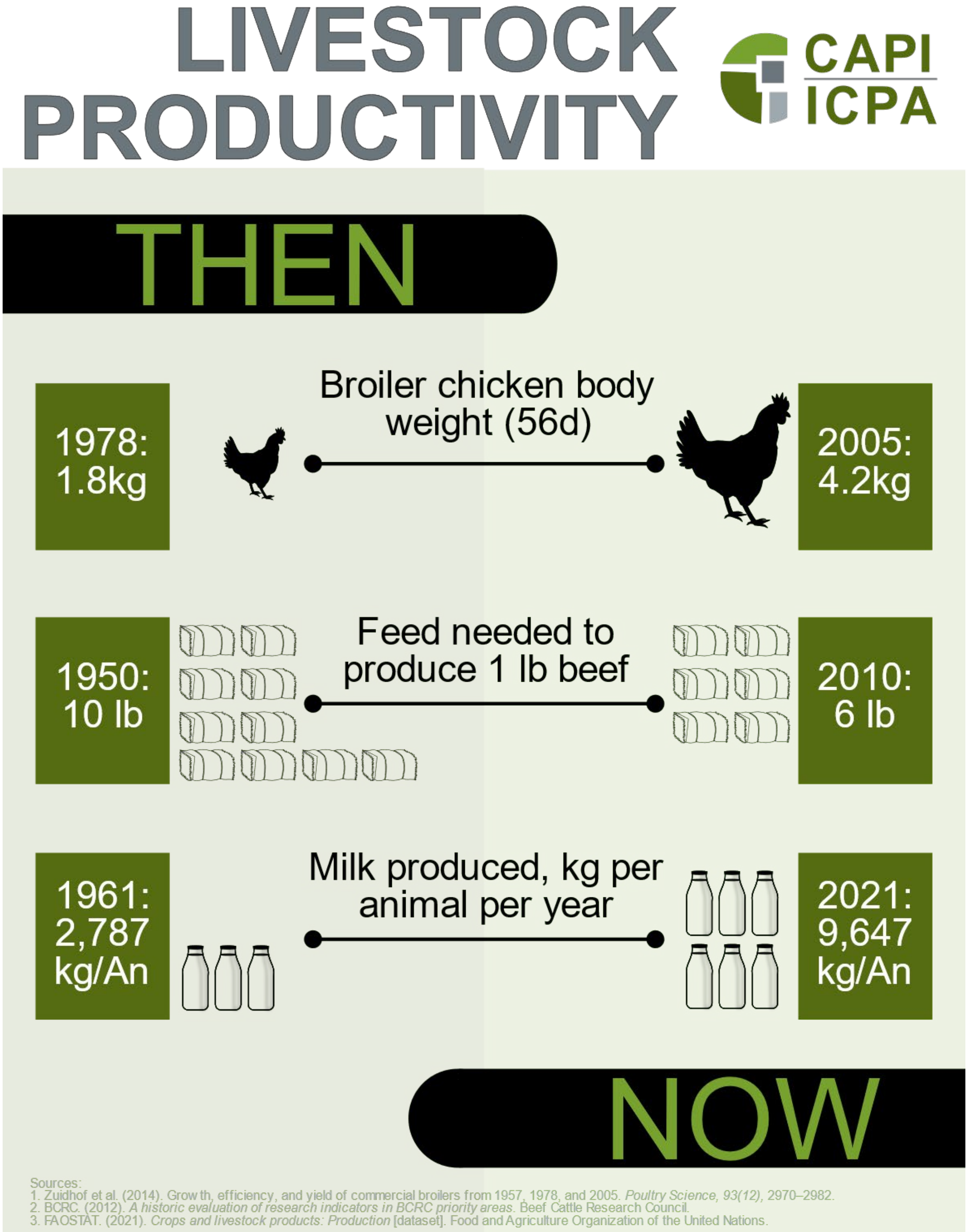


Image created internally.

8.3.1 Precision Technologies in Animal Agriculture

Aquilani *et al.* (2022) defined precision livestock farming as “the combined application of single technologies or multiple tools in integrated systems for real-time and individual monitoring of livestock” (p. 1). These technologies are deployed in a variety of applications, both in confined animal production and in grazing systems. They are also commonly connected to or combined with decision support systems.

Gómez *et al.* (2021) assessed precision technologies for use in monitoring pig welfare. Their review considered the following precision technologies in a review of advanced approaches to swine welfare:

- camera-based technologies
- load cells and flow meters
- accelerometers
- microphones
- thermal cameras
- photoelectric sensors
- RFID technologies for animal identification
- non-contact body sensors

They observed that “a variety of animal-based welfare indicators can be monitored on an individual scale, continuously and in real time” using these tools (p. 16).

Aquilani *et al* (2022) reviewed precision technologies in pasture-based systems. They explored many of the technologies above, mostly with grazing cattle, and also examined virtual fencing to implement intensive grazing management. They observed that “positive outcomes in terms of rangeland conservation, animal welfare, and labour optimization are expected from the spread of precision livestock farming in grazing systems” (p. 1).

Zuidhof (2020) discussed the prospects for precision feeding technologies in poultry to better match feeding with the dietary needs of individual animals. Individual tailored feeding could greatly improve retention of nitrogen, phosphorus and other nutrients in poultry diets; systems have been developed to implement individual feeding for broiler breeder operations, and are being developed for more general application in poultry (M. Zuidhof, 2020). In swine, Andretta *et al.* (2016) found that precision feeding reduced digestible lysine intake by 26%, and reduced nitrogen excretion by 30% and feeding costs by about 10% relative to group feeding.

Precision systems are also employed to identify disease and support decision making, and to increase labour productivity and gaps in labour supply. For example, Casella *et al.* (2023) investigated the use of precision technologies based on the Internet of Things (IoT), such as automatic feeders, scales, and accelerometers, to help detect behavioural changes before outward clinical signs of Bovine Respiratory Disease. Their results showed an accuracy of 88% for labelling sick and healthy calves, with 70% of sick calves predicted 4 days prior to diagnosis, and 80% of persistency status calves are detected within the first five days of sickness – an improvement relative to other approaches (Casella *et al.*, 2023).

Malacco (2022) developed an overview of the effect of automated milking systems using robotics in the dairy industry. His overview noted important advantages of spared labour in milking, but also remarkable data and information that is collected on individual cow health, welfare, behaviour, and nutrition that is valuable for management decisions. Malacco notes studies observing a milk production increase of 5 to 10 percent with automatic milking systems versus conventional twice-daily milking systems, and a 20 percent decrease in the number of employees (Malacco, 2022). Robotic milking systems also have an important social sustainability aspect. Vik *et al.* (2019) analyzed the adoption of robotic milking systems in Norway and observed that, while the economic returns were mixed, “Norwegian farmers invest in milking robots to improve their everyday life – socially and professionally – and they increase the production to finance their investment” (p. 1).

8.3.2 Reproductive Technologies

Georges *et al.* (2019) reviewed studies of genomic applications in livestock. They observed that "Over the past 10 years, genomic selection has been introduced in several major livestock species, and has more than doubled genetic progress in some" (p. 1). One illustration is that the process for obtaining estimated breeding values for individual animals for individual animals can be dramatically shortened using genomic methods, provided that sufficient data exists for a background reference. For example, Georges *et al.* observe that in cattle, genomic methods allow genetic data to be made available 5 years sooner, and with much greater accuracy on low heritability traits.

Holden and Butler (2018) review the evidence of effects of sexed semen technology applied in the dairy and beef cattle production. They found that "Sex-sorted semen is a revolutionary technology for cattle breeding. Greater utilization of sexed semen can increase the efficiency of both dairy and beef production, increase farm profitability and improve environmental sustainability of cattle agriculture" (p. s97). More specifically they observed "increased genetic gain in dairy herd, increased value of beef output from the dairy herd, and reduced greenhouse gas emissions from beef" (p. s97). However, Holden and Butler worry that even small reductions in fertility with sexed semen could negate the economic benefit.

8.4 Observations

Canadian animal agriculture has made impressive gains in productivity and output, distributed across animal industries. These have occurred as research effort and innovation has occurred targeting critical bottlenecks. The fundamental bottleneck is conversion efficiency, which ultimately maps back to the agricultural land base that supplies animal feedstuffs. It also relates to the foundation breeding herd/flock, and also to the use and availability of human resources in livestock agriculture. Progress is ongoing addressing these fundamental bottlenecks, which involves a broad spectrum of factors: nutrition, epidemiology, housing, animal husbandry, and management/economics. Impressive developments in animal genetics and breed, along with precision data capture and automation, have supported this progress.

There are also specific challenges and problems of animal agriculture, much of which falls within the purview of conversion efficiency. For example, manure emissions can readily result in offsite losses of nitrogen and phosphorus, which (in addition to offsite damages) implies a loss of plant nutrients and growth potential, and ultimately a loss of animal feedstuffs; this connects animal emissions with land use efficiency. Animal diseases also impact conversion efficiency, but with potentially much greater impacts related to export market access.

In many cases, the challenges and problems of animal agriculture cannot be readily contained within the farm or the industry value chain, nor focused solely on conversion efficiency – and research and innovation must target these explicitly. Work is well established and ongoing to measure, understand pathways, and develop innovations that will reduce the unintended effects of emissions from livestock agriculture. Thorough data is collected and shared on the use of animal health products, with industry initiatives for judicious use of the products most of concern for resistance, and alternatives to certain antimicrobial products actively pursued, such as through vaccines and phage animal health products.

Perhaps the most challenging problem is biological system overload, and the unintended pursuit of conversion efficiency at the exclusion of animal function, and ultimately of animal resilience. As discussed above, conversion efficiency is fundamental to sustainable land use, and ambition in animal development focused on conversion efficiency is critical. The extent to which this can or should be traded off with non-productive aspects is the subject of development, consistent with some aspects of improved animal welfare and with resilience to prospective future challenges such as new diseases and extreme weather.