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INVITED REVIEW

The role of livestock in sustainable food production systems in Canada

Kim Ominski, Kebebe Gunte, Karin Wittenberg, Getahun Legesse, Genet Mengistu, and Tim McAllister

Abstract: Global drivers such as the growing human population, evolving consumer preferences, globalization, and climate change have put pressure on the agri-food sector to produce more livestock products with less land, feed, and water. Taste, nutritional value, cost, convenience, source, animal welfare, and environmental sustainability of food are criteria upon which purchasing decisions are made. In response, an environmental footprint analysis composed of greenhouse gas emissions, nutrient and water use efficiency, water quality, carbon storage, and biodiversity has been completed for many commodities. However, as livestock production systems occur within complex agro-ecosystems, it is extremely challenging to formulate a single overall sustainability metric. There is no "silver bullet" to solve the environmental concerns of all livestock production systems as they operate under different constraints on different landscapes, with different water and nutrient cycles, and soil types. Furthermore, the lack of scientific evidence regarding the interactions between livestock production, human nutritional adequacy, and the health of our environment makes it difficult for consumers to interpret this information and make informed food choices. This review examines these complex interactions and trade-offs, as well as the potential impacts of changes in consumer dietary choice on environmental sustainability, nutritional adequacy, and land use.

Key words: livestock, sustainability, environmental footprint, Canada.

Résumé : Des facteurs mondiaux comme la population humaine croissante, l'évolution des préférences des consommateurs, la mondialisation, et les changements climatiques font pression sur le secteur agroalimentaire pour produire davantage de produits du bétail avec moins de terrain, d'aliments, et d'eau. Le goût, la valeur nutritionnelle, les coûts, la commodité, la source, le bien-être animal et la durabilité environnementale de la nourriture sont les critères selon lesquels les décisions d'achats sont effectuées. En réponse, une analyse de l'empreinte environnementale composée des émissions de gaz à effet de serre, de l'efficacité d'utilisation des éléments nutritifs et de l'eau, de qualité d'eau, du stockage du carbone et de biodiversité a été complétée pour de nombreux produits. Par contre, comme les systèmes de production de bétail surviennent à l'intérieur d'agroécologies complexes, c'est un défi extrême de formuler une seule mesure générale de durabilité. Il n'y a pas de solution miracle pour résoudre les questions environnementales de tous les systèmes de production de bétail puisqu'ils fonctionnent sous différentes contraintes dans des paysages différents, avec différents cycles d'eau et d'éléments nutritifs, et de types de sols. De plus, le manque d'évidence scientifique au sujet des interactions entre la production du bétail, la suffisance nutritionnelle pour les humains, et la santé de notre environnement rend difficile l'interprétation de cette information par les consommateurs afin qu'ils puissent effectuer des choix alimentaires éclairés. Cette revue évalue ces interactions et compromis complexes, ainsi que les impacts potentiels des changements de choix alimentaires du consommateur sur la durabilité environnementale, la suffisance nutritionnelle, et l'utilisation des terrains. [Traduit par la Rédaction]

Mots-clés : bétail, durabilité, empreinte environnementale, Canada.

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Introduction

A resilient and sustainable food production system that conforms to the nutritional, health, and environmental expectations of consumers is a laudable goal, but one that presents many challenges to the agri-food sector. Particularly problematic is the challenge to measure and communicate science-based information regarding the role of livestock in complex agro-ecosystems. The intent of this review is to highlight key drivers regarding protein production and consumption, including environmental sustainability and the introduction of meat alternatives. In addition, the importance of livestock as an essential element of a circular bioeconomy, leading to improved system sustainability, will be addressed.

Global Drivers Impacting Animal Protein Production and Consumption

The agricultural sector is faced with the daunting challenge of producing food for a growing global population, which is expected to reach 8.5 billion by 2030, 9.7 billion by 2050, and 11.2 billion by 2100 (Roser et al. 2019), with sub-Saharan African countries accounting for more than half of the growth of the world's population between 2019 and 2050 (Fig. 1; Roser et al. 2019).

Population growth along with increased socio-economic status and urbanization (Mottet et al. 2017) are expected to increase global demand for meat and dairy by 57% and 48%, respectively, between 2005 and 2050 (Alexandratos and Bruinsma 2012). The majority of growth is expected to occur in developing countries (Mottet et al. 2017). The East and Southeast Asian region is expected to realize income growth of 60%–100% per capita by 2028, resulting in an increase in the consumption of meat by 5 $kg{\cdot}capita^{-1}$ in China and 4 $kg{\cdot}capita^{-1}$ in Southeast Asia, largely from poultry and pork. Beef consumption in China is also expected to rise by 0.5 $kg{\cdot}capita^{-1}$ over the next decade, bringing average consumption to 4 $kg{\cdot}capita^{-1}$. In South Asia, income growth is projected to be associated with greater consumption of dairy products, sugar, and vegetable oil. Dairy products and pulses will remain important sources of protein within this region. Pakistan is expected to lead global dairy consumption growth, with annual consumption of 274 $kg{\cdot}capita^{-1}$, providing nearly 30% of the total daily per capita protein requirement. Dairy consumption is projected to grow in India as well and will account for 15% of total per capita protein intake by 2028 (OECD–FAO 2019). Growth in the global demand for animal-based protein could present export market opportunities for Canadian livestock producers. The Conference Board of Canada (2017) has suggested that given Canada's reputation in food quality and security, the export potential is significant as a result of demand from Asia and other fast-growing markets.

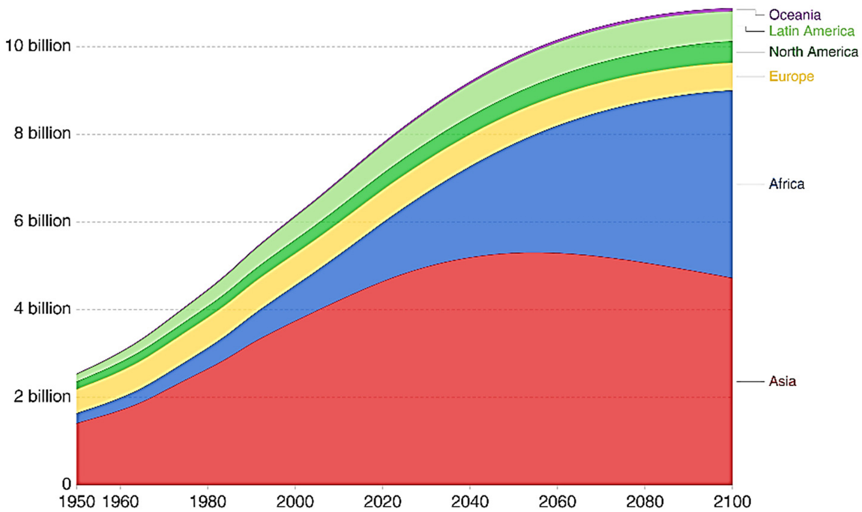
Consumer Preferences and the Nexus Between Diet, Nutrition, and Health

Links between diet, nutrition, health, and environmental sustainability have increased the complexity of diet selection for consumers as they search for a sustainable diet (Layman 2018). The Food and Agriculture Organization of the United Nations (FAO) defines sustainable diets as those with "low environmental impacts which contribute to food and nutritional security and to a healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, cultural preferences, accessible, economically affordable, nutritionally adequate, safe and healthy, while optimizing natural and human resources" (FAO 2010). The sustainability of animal-based diets has been widely questioned, with an emphasis on the adoption of plant-based diets to reduce global agricultural greenhouse gas emissions, combat land-use change, and improve human health outcomes (Tilman and Clark 2014; Willett et al. 2019). A recent Canadian survey ($n = 1029$) revealed that more than 48% of respondents stated that they consume meat daily, whereas 40% consume meat once or twice per week (Charlebois et al. 2020). Furthermore, 82% stated that they do not have dietary restrictions, 10% considered themselves flexitarians, 1.2% were pescetarian, 1.1% were vegan, 1.2% were lacto-ovo vegetarian, and 2.1% were vegetarian (Charlebois et al. 2020). Similarly, data from the Canadian Community Health Survey also indicated that 5% of Canadians excluded red meat from their diet (Gunte et al. 2020). These publications align with per capita consumption data indicating that consumption of beef, pork, and fluid milk has decreased, whereas consumption of chicken has increased in Canada.

Key attributes driving purchasing decisions and consumption patterns of consumers include cultural appropriateness, taste, nutritional value, cost, source, availability, ethical considerations, and environmental sustainability of food products. A review including 30 published articles ($n = 19\,040$ participants) examined consumer preference for food labeling based on attributes of nutrition, environment, and social responsibility (Tobi et al. 2019). These authors reported that environmental and social responsibility claims were preferred to nutrition attributes in 17 studies (11 environmental and six social), whereas nutrition attributes were favored in nine studies. Three studies found a combination of attributes were preferred, with no preference indicated in a single study. Organic labeling was deemed to be the most important attribute (Tobi et al. 2019). Such surveys emphasize the diversity and variability that is inherent within consumer preference.

The nutritional attributes of livestock commodities are well documented in the published literature but are less clear to consumers as they seek unbiased

Fig. 1. World population by region projected to 2100, based on the United Nation's medium population scenario (Roser et al. 2019). [Colour online.]



information regarding the impact of diet choice on nutrient adequacy and health. Animal-based products, including meat, dairy, and eggs, have high nutritional value and are an important source of protein and essential amino acids (Layman 2018). For example, red meat is a source of several essential trace nutrients, including B vitamins, with B_{12} obtained exclusively from animal sources, as well as A, D, and K_2 (organ meats) and various minerals with zinc, selenium, and iron that are often more available in animal than plant-based protein (Williamson et al. 2005; Williams 2007; Rooke et al. 2010; Pereira and Vicente 2013; Wyness 2016; Leroy and Cofnas 2020). Further, red meat is rich in essential amino acids, i.e., methionine, threonine, and lysine (Leroy and Cofnas 2020), and long-chain omega-3 fatty acids, i.e., eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Cholewski et al. 2018), which are deficient in plant-based diets. These bioactive components as well as others play an important role in cognitive function (Leroy and Cofnas 2020), energy metabolism, and immunity (Binnie et al. 2014). Animal-based food products provide a significant portion of the essential fatty acids (23%–100%) and essential amino acids (34%–67%) available to meet the nutritional requirements of Americans (White and Hall 2017).

Red meat intake has been linked with increased blood cholesterol level, risk of coronary heart disease (CHD), and some forms of cancer. However, the association between red meat consumption and health has been inconsistent, attributable to differences in experimental approaches, degree of processing, cut and cooking method (Pereira and Vicente 2013; McNeill 2014; O'Connor et al. 2017). As summarized in Binnie et al. (2014), epidemiological studies conducted over the last decade in North America and Europe have found no association between the consumption of unprocessed meat and cardiovascular disease or cancer (Kappeler et al. 2013; Rohrmann et al. 2013), as well as coronary heart disease (Micha et al. 2010). A number of recent surveys and meta-analyses have also assessed the linkage between cardiovascular disease and red meat consumption. For example, O'Connor et al. (2017) analyzed 24 randomized control trials with subjects aged 19 yr and older, and they concluded that consumption of $\geq 35\ g \cdot d^{-1}$ of red meat did not influence blood lipids and lipoproteins or blood pressure compared with consumption of $< 35\ g \cdot d^{-1}$. Further, recommendations regarding restrictions on red meat intake must consider nutrient requirements for all segments of society, including young children, adolescents, women of childbearing age, as well as aging populations in which protein and micronutrient intake may be less than optimal (Wyness 2016). Although dietary advice to limit red meats remains standard in developed countries, energy intake from processed food has increased at the expense of nutrient-rich foods — a dietary trend that has negative health consequences including obesity and other associated diseases such as diabetes (Binnie et al. 2014). As highly processed, ready-to-consume foods have become increasingly available, it is paramount to ensure that recommendations to restrict meat consumption do not lead to increased intake of highly processed carbohydrate-rich foods that are often high in salt and sugar but low in essential nutrients (Binnie et al. 2014).

Recently, methionine-reduced diets have been linked to longevity in animal studies (Kitada et al. 2021). As animal sources of protein, such as beef, lamb, fish, pork, and eggs, contain higher levels of methionine than plant-sourced proteins (Schmidt et al. 2016), it has been proposed that the level in the diet be restricted. However, it is not known if restricted methionine intake has beneficial effects on aging in humans (Kitada et al. 2021). As methionine is an essential amino acid for humans, the restriction could also increase the risk of deficiency.

Animal-based food products are not only a valuable source of micronutrients but also account for 18% of global caloric and 25%–33% of protein consumption by humans (Food and Agriculture Organization Corporate Statistical Database 2016; Layman 2018). The Food and Agriculture Organization Corporate Statistical Database 2016 has identified an inverse relationship between the inclusion of animal-sourced foods ($g \cdot d^{-1}$) in the human diet and the global hunger index (FAO 2018). Simulated removal of livestock from the human diet in the US (White and Hall 2017) was predicted to result in excess dietary energy and increased nutrient deficiencies for American consumers. Similarly, respondents who reported less meat and dairy or no meat and dairy consumption in France, had lower intake of protein and several micronutrients, suggesting a potential increased risk of deficiencies (Seves et al. 2017). Although it has been suggested that reducing or eliminating livestock production would result in increased food production and more calories per person (Cassidy et al. 2013), chronic health issues related to excessive caloric intake do not align with the underlying goal of achieving global food security.

Food choices that are not informed by sound science may also have unintended negative consequences on environmental sustainability. Beef raised without the use of productivity-enhancing technologies, such as hormones and implants, has captured the attention of consumers, although it has been demonstrated that meat does not play a significant role in the daily intake of steroid hormones compared with human production of these compounds (Hartmann et al. 1998). Further, studies in the US (Capper and Hayes 2012) and Canada (Basarab et al. 2012) have shown that the use of productivity-enhancing technologies results in a 5%–10% reduction in greenhouse gas (GHG) and ammonia emissions, as well as a 10% reduction in the amount of land required to produce the same quantity of beef. In addition, a simulation study examining the impacts of removing animals from the agricultural production system on total US GHG emissions estimated a nominal reduction in emissions of 2.6% with a considerable reduction in diet quality (White and Hall 2017). Consumer interest in environmental sustainability, coupled with government policy initiatives to reduce GHG emissions, has led to an examination of the carbon footprint of both animal- and plant-based agricultural commodities. However, these footprints are often incomplete and do not consider all GHG sources and sinks within complex integrated livestock and crop production systems.

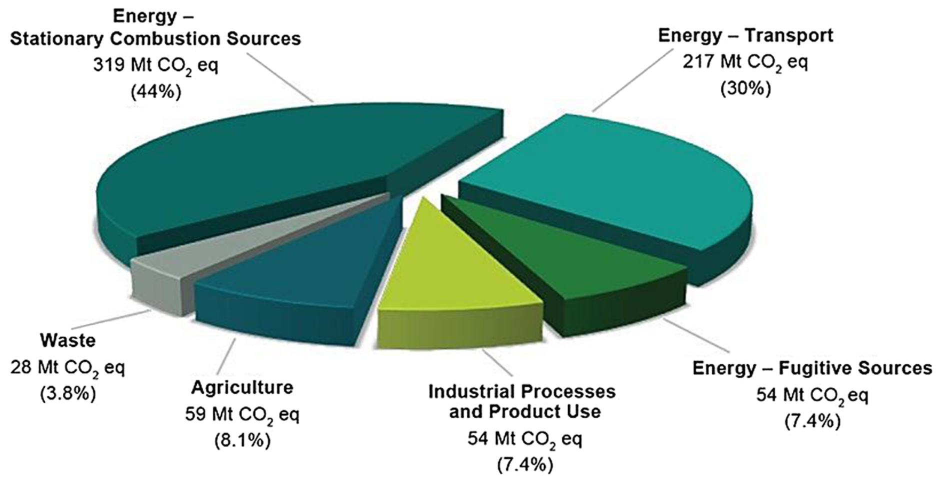
Environmental Footprint of Animal-based Products in Canada

An environmental footprint of a product involves an evaluation of sustainability indicators including GHG emissions, nutrient balance, land and water use efficiency, water quality, carbon storage, and biodiversity throughout the production chain. The functional unit selected to estimate GHG emissions (i.e., net or intensity basis) can significantly influence the carbon footprint associated with any given food type. For example, GHG emissions from the production of processed fruits and vegetables expressed on a weight basis were lower than meat and meat products, milk and dairy products, grain and other foods, as well as sweets (Drewnowski et al. 2015). However, when expressed per 100 kcal of energy, vegetables had higher emissions than meat or dairy products. Several studies have also examined the relationship between the nutrient density of foods and GHG emissions, demonstrating that animal-based foods have consistently lower emissions on an intensity basis for energy (Vieux et al. 2013), protein (Veeramani et al. 2017), or overall nutrient density (Werner et al. 2014) on a per weight basis. Assessments of the role of meat and milk products in a sustainable diet are often based on GHG emissions expressed as $kcal^{-1}$ of food produced, leading to the conclusion that livestock have a greater negative impact on the environment than plant-based diets. This approach is also based on the misguided assumption that calories are more important than dietary protein (Layman 2018). Therein lays the limitation of using a single metric to assess the environmental impact of food products.

In Canada, agriculture accounts for 8.1% of total GHG emissions (Fig. 2; Environment and Climate Change Canada 2021) while energy from all sources including transport accounts for 81.6% of emissions, the remainder associated with industrial processes (7.7%) and waste (2.4%). As a consequence, CO_2 is the largest contributor to total emissions (80%), the majority of which arise from the combustion of fossil fuels. Emissions from livestock digestion accounted for less than half of all agricultural emissions, representing 3.3% of total Canadian GHG emissions in 2018. Despite the comparatively lower emissions compared with some other sectors, considerable effort has been expended in estimating the environmental footprint of beef, dairy, and eggs.

Over a 30 yr time period (1981–2011), Canadian beef producers have reduced GHG emissions (kg^{-1} carcass) by 15% (Legesse et al. 2016), ammonia emissions by 17% (Legesse et al. 2018*a*), water use by 20% (Legesse et al. 2018*b*), while using 24% less land (Legesse et al. 2016). Similarly, in another study conducted in the US, the nation's beef industry in 2007 required 30% fewer beef cattle, 22% less water, and 33% less land, with a 16% decline in the carbon footprint per kilogram of beef than in 1977 (Capper 2011). An environmental footprint has

Fig. 2. Breakdown of Canada's greenhouse gas emissions by sector in 2019. Reprinted from Environment and Climate Change Canada (2021). [Colour online.]



also been conducted for milk in Canada. Over a 20 yr period (1991–2011), fat- and protein-corrected milk (FPCM; $kg \cdot cow^{-1} \cdot yr^{-1}$) production increased by 43%, whereas enteric methane (kg $CO_2 \cdot kg^{-1}$ FPCM) and total emission intensity (kg $CO_2 \cdot kg^{-1}$ FPCM) decreased by 22% (Jayasundara and Wagner-Riddle 2014). Similarly, Pelletier (2018) examined the environmental footprint of the egg industry from 1962 to 2012 and reported a 57% decrease in industry total GHG emissions, with energy, land, and water use decreased by 10%, 71%, and 53%, respectively.

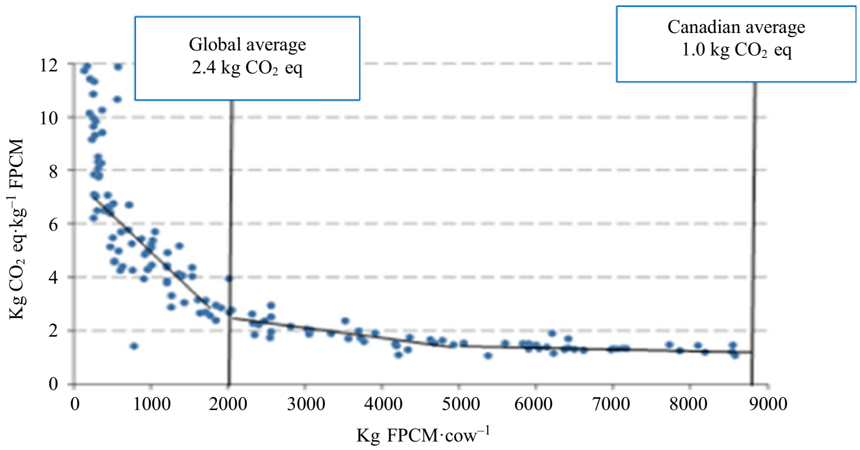
Many commodity groups in Canada have implemented on-farm food safety programs which have expanded to include metrics associated with animal care, biosecurity, environmental stewardship, traceability, and human resource management. Commodity chains have also developed and communicated industry goals to the general public to demonstrate efforts for continuous improvement in several areas of environmental sustainability. For example, organizations involved in Canada's National Beef Strategy which include the Beef Breeds Council, Beef Cattle Research Council, Canada Beef, The National Cattle Feeders' Association, Canadian Meat Council, and Canadian Roundtable for Sustainable Beef (Canadian Beef Strategy 2020) recently announced a new set of industry goals for 2030 in the areas of GHG and carbon sequestration, animal health and welfare, and land use and biodiversity. These steps to benchmark current practices and develop and implement best management practices that further heighten environmentally favorable and clearly sustainable outcomes will be key to retaining the social license needed for livestock production.

Improvements in emission intensities in all livestock sectors have occurred as a result of improvements both in animal productivity (reproductive efficiency, weaning weight, and carcass weight) and crop yields (barley grain, barley silage, corn grain, and corn silage), irrigation efficiency (Legesse et al. 2016; Legesse et al. 2018*b*), as well as improved genetic selection, disease management, precision feed formulation, and feeding technology. Production intensity and emission intensity are inversely related, and therefore, the use of precision technologies that enhance the efficiency of livestock production systems can improve sustainability.

An additional outcome of these studies is an examination of the use of human-edible vs. -inedible ingredients in livestock diets. Legesse et al. (2016) estimated that approximately 80% of the feedstuffs that cattle in Canada consume over their lifetime are forage based. Much of this forage is produced on pasture which comprises nearly one-third of all the agricultural land in Canada and is often unsuitable for crop production. Canadian values are consistent with those reported globally, where approximately 70% of all agricultural land is grassland that can only be utilized by ruminant livestock (FAO 2013). Approximately 86% of the 6 billion tonnes of feed consumed annually (including one-third of annual global cereal production) is considered unsuitable for human consumption, with 57% of the land used for feed production being unsuitable for food production (Mottet et al. 2017).

A novel approach to assess the sustainability of livestock production systems is a comparison of global feed conversion ratios [metric tonnes $protein \cdot yr^{-1}$, kg dry matter ($DM) \cdot kg^{-1}$ protein, kg edible $DM \cdot kg^{-1}$ protein, kg edible $DM \cdot kg^{-1}$ meat, kg complete $DM \cdot kg^{-1}$ protein, and kg edible $protein \cdot kg^{-1}$ protein] as described by Mottet et al. (2017). Using these metrics, Mottet et al. (2017) estimated that on a global basis, an average of 2.8 and 3.2 kg of potentially human-edible feed are required to produce 1 kg of boneless meat in ruminant and non-ruminant production systems, respectively. Thus, ruminants are more efficient than non-ruminants if human

Fig. 3. Average greenhouse gas emissions associated with annual milk production globally and in Canada. Modified from Gerber et al. (2011). [Colour online.]



inedible feed sources are used. Another novel avenue for examining the value of animal-based protein in meeting human protein requirements has been proposed by Baber et al. (2018), who developed a model to estimate net protein contribution by multiplying the ratio of human-edible protein (HeP) in beef to HeP in feedstuffs by a protein quality ratio, derived from the change in biological value of HeP that occurs when plant-derived HeP is converted to beef. There were sectoral differences in HeP and methane production, with low HeP conversion efficiency for some scenarios using grains as a major feed component (stocker and feedlot). However, the ability of cattle to convert low-quality protein to high-quality protein resulted in a positive net protein conversion, which is the case when forage and by-products are fed to cattle. Therefore, these authors concluded that the beef industry produces more high-quality HeP than is consumed.

The geographical location of production can result in significant differences in emissions per unit of food product as there is significant variation in net emissions from agricultural systems in developing and developed nations, resulting in differences in the emission profile of specific commodities such as milk (Gerber et al. 2011). Milk produced in Canada has a footprint of 1.0 kg CO_2-eq·kg^{-1} milk (Vergé et al. 2013), whereas the global average is 2.4 kg CO_2-eq·kg^{-1} milk (Fig. 3; Gerber et al. 2010).

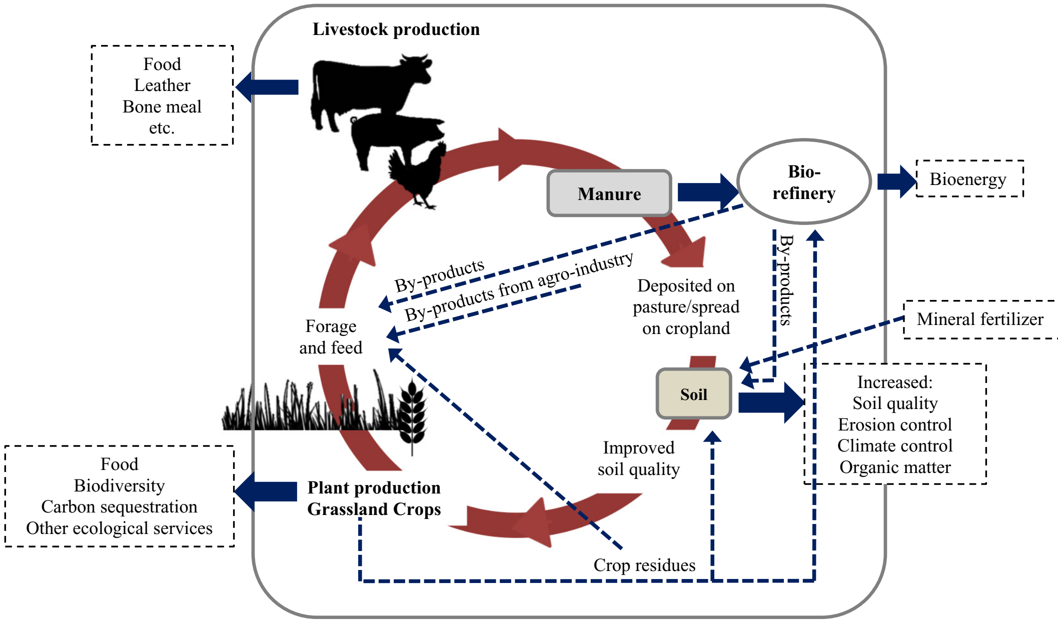
Role of Livestock in a Circular Bio-economy

Most often, environmental footprints examine only one or two sustainability indices associated with complex agro-ecosystems as it is extremely challenging to establish a single value to assess overall sustainability. Elements of livestock production systems, including carbon sequestration, biodiversity, and other ecosystem services, are metrics that are often overlooked in life cycle analysis and environmental footprinting. With such a wide variety of factors influenced by animal agriculture, it is difficult to measure and communicate to the public the role of these diverse and multi-functional production systems in a "circular bio-economy" (Fig. 4; Ward et al. 2016). The concept of a "circular bio-economy" focuses on the production of agricultural commodities with minimal external inputs, closing nutrient loops, and reducing negative impacts on the environment in the form of wastes and emissions. Understanding the circularity of agricultural systems has the potential to identify opportunities to apply precision technologies to enhance recycling and utilization of agricultural waste throughout the production system (Ward et al. 2016).

The ruminant production system is one in which human-indigestible biomass, including grasses and forages, crop residues, grain screenings, by-products from commodity processing, and foodstuffs that fail to meet the quality standards for human consumption are converted to high-quality protein in the form of meat and milk. As a consequence, cattle are often referred to as "up-cyclers", upgrading inedible plants and plant by-products to high-quality protein and essential micro-nutrients, vitamins, and minerals.

In addition to serving as a valuable source of nutrients, numerous by-products are garnered from livestock including hides, tallow, blood, hooves, horns, organs, and bones. These by-products are utilized to produce marketable commodities including pharmaceuticals, cosmetics, leather, brushes, adhesives, charcoal, shampoo, glass, and pet food (Farm and Food Care Ontario 2016; Lynch et al. 2018; North American Renderer's Association 2020). Using the entire edible protein content from farmed animals, including currently underused meat co-products to meet the protein requirements of the global population could further improve environmental sustainability (Lynch et al. 2018). In the US, it has been estimated that if cattle were

Fig. 4. Livestock and sustainable agriculture: the circular bio-economy (Ward et al. 2016). [Colour online.]



removed from the landscape, 43.2×10^9 kg of human-inedible food and fiber by-products would no longer be converted into human-edible food, pet food, or industrial products (White and Hall 2017). In addition to the loss of a key protein source, many plant by-products normally fed to animals would be directed to landfill adversely affecting our environment.

Livestock manure is an important element of a circular bio-economy as it is an important source of organic matter, nitrogen, phosphorus, and trace elements that are essential for soil health and plant growth. Manure incorporation into the soil also reduces the need for commercial chemical fertilizers, lowering the use of fossil fuels that are required for their production. In 2018, nitrogen excreted in livestock manure was estimated at 6.2×10^{10} kg globally and 5.6×10^8 kg in Canada (FAO 2018). In the US, it has been estimated that manure contributes 4×10^9 kg of nitrogen fertilizer (White and Hall 2017). Implementation of best management practices, including manure injection in soil, reduced time of storage, and use of storage covers, has served to reduce GHG emissions (VanderZaag et al. 2008; Montes et al. 2013).

The economic and environmental merits of integrated-crop livestock production systems, including the use of manure, have been well documented in conventional and organic production systems (Russelle et al. 2007; Entz and Thiessen-Martens 2009; Kumar et al. 2019; Carr et al. 2020). Manure can be excreted directly on pasture or collected from intensive livestock production systems where it may be subject to secondary processing procedures such as stockpiling, composting, or dewatering prior to land application. Manure may also be used as a fuel, either by drying and combustion or as a substrate in biodigesters that generate biogenic methane (FAO 2018).

In addition to the micro and macronutrient value and associated increases in crop yield, livestock manure can significantly increase soil organic matter, a key factor of soil health, promoting soil microbiota diversity, and enzyme activity (Larney and Angers 2012; Ozlu et al. 2019). Finally, perennial forages utilized by ruminants have the capacity to serve as a reservoir for carbon as plant root biomass and recalcitrant plant tissue contribute to soil organic matter. Capture of atmospheric carbon through photosynthesis and accumulation of plant carbohydrates in soils constitutes carbon sequestration, with the stability of carbon depending on soil management, microbial–carbohydrate interactions, deposition depth, and environmental conditions. Grazing of grasslands in Canada has been estimated to constitute a net carbon sink in the top 15 cm depth with an average net carbon sequestration of 5.64 ± 0.97 Mg carbon·ha^{-1} (Wang et al. 2014). In addition to increasing soil nutrient and organic matter, perennial forage cover and deposition of manure on pasture can help mitigate soil erosion (Lobb et al. 2016) and can increase soil moisture (Omokanye 2013), with subsequent benefits in crop yield (Jungnitsch et al. 2011).

From a global perspective, the role of livestock extends beyond nutrition, having social, economic, cultural, and political implications in developing countries (Riethmuller 2003). Not only do they provide essential nutrients for early childhood cognitive development, but livestock also have the potential to be “transformative” providing cash necessary for food staples, farm inputs, and education, as well as draft power while producing manure as a fertilizer (Smith et al. 2013).

In addition to diet selection, as consumers, we all have a role to play regarding the environmental impact associated with food waste. Globally, food waste and loss is staggering — with losses of 30% for cereal foods, 45% for fruits and vegetables, 20% for oilseeds and pulses, 45% for roots and tubers, 20% for dairy products, 30% for fish and seafood, and 20% for meat (Mottet 2019). In Canada, total avoidable and unavoidable annual waste along the food value chain is estimated to be 35.5 million metric tonnes, 32% of which is avoidable and valued at $49.5 billion. This represents 51.8% of the money Canadians spend on food, 3% of Canada's 2016 GDP, and enough food to sustain every person in Canada for almost 5 mo (Gooch et al. 2019). Potential inclusion of food waste in livestock diets is a preferred strategy for food waste management, as compared with composting or disposal of food wastes in landfills. However, there is a paucity of data available regarding the magnitude of this practice in Canada, and additional research is necessary to examine the full potential of using food waste streams in livestock diets.

Meat Alternatives

Environmental and welfare concerns regarding livestock production systems have resulted in a call for a shift to plant-based diets (Springmann et al. 2018; The Global Resource for Nutrition Practice 2019; Willett et al. 2019), leading to changes in national food guides in Canada and elsewhere. This has resulted in the development of emerging markets focused on plant-based, microbial, insect, and laboratory-grown protein alternatives. Although plant-based protein sources are not new, plant-based meat analogues, and more recently cell-based meats created using cell cultures and tissue engineering technology, are recent innovations developed to mimic meat derived from traditional livestock-based production systems. Introduction of these products has led to complex questions regarding environmental sustainability, health, cultural, and economic impacts of these protein production practices as compared with animal-based systems (Broad 2020). Unintended negative impacts and potential nutritional challenges of these products have been identified as a consequence of differences in nutrient profile between plant- and animal-based diets (Ertl et al. 2016; Bohrer 2017). Consumer acceptance of these products has also been questioned given that livestock muscle is required to produce stem cells, and hormones and growth promoters (which are banned in conventional production systems in several countries) are necessary to facilitate cell proliferation and differentiation (Chriki and Hocquette 2020). Antimicrobials are also often used to prevent bacterial contamination of cell cultures. Other challenges associated with cellular meat products include taste, texture, and cost, as well as required changes in regulation and labeling (Warner 2019). Nutritional profiles may be unbalanced (Broad 2019), availability in remote locations could prove challenging, and removal of livestock from the land would alter livelihoods while disrupting social and cultural practices. Economic impacts in integrated livestock–cropping systems would be significant, and health professionals and dieticians would require training to ensure that diets that contained cultured meat were balanced to meet nutrient requirements (The Global Resource for Nutrition Practice 2019).

Future Direction

Livestock and poultry production systems are part of a circular bio-economy from which our food is derived, with both environmental impacts and benefits. The complexity of these agro-ecosystems has made it difficult to evaluate and compare overall production system sustainability based on multiple environmental indicators. Although we have refined our ability to measure complex environmental metrics such as biodiversity and carbon sequestration, we do not have a mutually agreed-upon public vision for their valuation. This impacts our ability to alter management strategies as public priorities change more quickly than food production systems. More recently, the intersect between diet, environment, and health has further widened and complicated sustainability assessments, as it is impossible to develop a single metric to assess the myriad of factors that constitute a sustainable diet. Therefore, although sustainable production systems and diets are important for human and environmental well-being, there is no "silver bullet" approach to define the trade-offs that exist between environmental health, human health, economic feasibility, and cultural preferences of the Canadian consumer.

Social media has facilitated global communication regarding the impact of agriculture and food production systems on the environment, often without recognition of the differences in management practices that exist in various regions of the world (e.g., Amazon rainforest and Prairie grasslands). Commodity chains including the production sector, as well as retailers and conservation groups, must continue to monitor and report nationally/regionally appropriate sustainability metrics to garner and maintain consumer confidence.

Not only they are the sustainability metrics difficult to measure, but they are also equally difficult to communicate to the general public. As stakeholders in the livestock sector, we are eager to share our knowledge with consumers. How we capture their attention is an ever-allusive challenge. Engagement between industry stakeholders and consumers in Canada has been facilitated through public programs including Agriculture in the Classroom, Open Farm Day, as well as national initiatives including the Canadian Centre for Food Integrity whose mandate is to coordinate research, dialogue, resources, and training in Canada's food system. There is an immediate need for dieticians, environmental/agro-ecosystem scientists, and policymakers to work together to inform public education and policy initiatives using science-based information to ensure optimal use of natural resources, nutritional adequacy, improved human health, and the environmental sustainability of Canadian diets. Multi- and trans-disciplinary collaboration is required to understand the complexity of food production and consumption and to develop and implement creative solutions to address environmental challenges. However, as we support consumers in their quest to make informed choices regarding diet, we must be mindful that there is room in the marketplace for a variety of food production systems.

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