Livestock—an essential component of a circular bioeconomy

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McAllister, T.A., Becquet, P., Amon, B., LEAP TAG and Lee, M.R.F. (2025) 'Livestock—an essential component of a circular bioeconomy' *Animal Frontiers*, *15*(4), pp.3-6.

Introduction

Livestock—an essential component of a circular bioeconomy

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Key words: biomass, circular bioeconomy, greenhouse gas emissions, livestock, sustainability

Sustainability of food chains may be improved when circularity principles are integrated, nutrients are retained in the food chain and biomass losses are reduced. In this context, redesigning livestock systems to more circular and regenerative approaches is a critical step. The foundation of this special issue arises from the United Nations Food & Agriculture Organization's Livestock Environmental Assessment & Performance (UN, FAO LEAP) Partnership who assembled a Technical Advisory Group of 36 experts from 23 different countries spread over five continents to investigate the role of livestock in circular bioeconomy systems. This special issue explores specifically the synergies, trade-offs, and interactions of livestock production within this context. Livestock play a fundamental role within a circular bioeconomy by converting nonedible biomass, such as pastures and forages, agricultural residues, and food industry byproducts into high-value animal-sourced foods Beyond food production, livestock systems support bio-based industries by valorizing animal byproducts (**ABP**) such as hides, bones, and fats into materials for pharmaceuticals, cosmetics, and bioenergy. Additionally, manure-based biogas production provides renewable energy while mitigating greenhouse gas (**GHG**) emissions. By recycling nutrients and utilizing low-opportunity-cost biomass, livestock contribute to reducing food-feed competition, enhance soil health, provide renewable energy and close nutrient cycles, improving the sustainability of agricultural systems and strengthening global food security. Furthermore, livestock play an integral role in promoting circularity in agricultural systems, a reflection of the coevolution of plant and animal agriculture over millennia. Not all livestock production systems optimize circularity and as a result transformative circular agricultural practices that promote the integration of crop–livestock–pasture systems that reuse, recycle, and valorize nutrients are needed to enhance sustainability.

McAllister et al. (2025a) outline the role of livestock in a circular bioeconomy and define how a circular bioeconomy lies at the intersection between the bioeconomy and the circular economy. Livestock play a critical role in the circular bioeconomy by upcycling animal- and plant-based byproducts, with the manure they produce contributing to nutrient cycling, soil health, and renewable energy generation. They outline that food-feed-fiber-energy competition should be minimized and when unavoidable, best management practices should be adopted to retain nutrients within the food system through a value pyramid approach. This approach supports most of the UN sustainable development goals (**SDGs**), including **SDG 2 (Zero Hunger)** by transforming inedible biomass—such as crop residues, pastures, food processing byproducts, and lands not suitable for cultivating crops—into high-quality animal-source foods that are nutrient-dense and support human and animal nutrition. It contributes to **SDG 12 (Responsible Consumption and Production)** by returning organic matter to soils, improving fertility, and reducing dependence on synthetic fossil-fuel/mined fertilizers. This nutrient cycling function also supports **SDG 13 (Climate Action)** when managed to mitigate methane and nitrous oxide emissions from manure and enhance soil carbon capture and sequestration. Moreover, livestock provide livelihoods for over a billion people globally, contributing to **SDG 1 (No Poverty)** and **SDG 8 (Decent Work and Economic Growth)**, especially in rural and marginalized communities. When integrated into agroecological and regenerative systems, livestock can promote **SDG 15 (Life on Land)** by maintaining grasslands, enhancing biodiversity, and supporting soil health. Thus, sustainable circular bioeconomy, livestock systems are not only

https://doi.org/10.1093/af/vfaf031

compatible with the SDGs but are essential for achieving a holistic, systems-based approach to global sustainability providing in concert to human and planetary health.

Halpern et al. (2025) emphasize the importance of developing holistic metrics that define the varying impacts of livestock on bioeconomy systems. Traditional metrics such as life cycle assessment, nutrient use efficiency, and feed conversion ratio allow for comparisons but fail to provide a holistic assessment. Holistic approaches such as the land use ratio metric can help define the impact of changing livestock feed sources on food-feed competition. Other holistic metrics can compare environmental indices such as GHG emissions as they relate to the production of meat and milk. Circularity measurements should also include social and economic dimensions. Evaluators also need to be cognizant of the possibility of second-order effects, where repurposing of byproduct can have an undesirable impact on other components within the system. Even when efficiencies are achieved, Jevons Paradox can negate benefits if resource use increases to meet expanded product demand, as such this must be protected against.

Lee et al. (2025) describe the numerous ABP that arise from carcass processing that can be recycled for direct consumption by humans, livestock or for other purposes such as pet food, fertilizer, soap, pharmaceuticals or renewable fuels. Combustion or landfilling of these byproducts is undesirable as these disposal methods lie at the bottom of the value pyramid and counter circularity and are responsible for environmental impacts. Rendering is a key process in the upcycling of ABP and the retention of nutrients within the food/feed chain. However, current limitations, mainly linked to regulatory restrictions in some countries, following the Bovine Spongiform Encephalopathy epidemic, reduce the potential of these rendered products for the circular bioeconomy. Appropriate regulations coupled with best management practices can ensure the production of safe food/feed, while environmental risks are managed. At the same time, maintaining the nutritional value of rendered products and sourcing them from animals declared safe for human consumption would enhance the potential for increased use of these valuable nutrients in livestock production. Regulatory differences and cultural preferences result in the use of co-products differing between countries, e.g., offal.

Ledgard et al. (2025) specify the numerous byproducts that arise from the processing of eggs and milk. Whey is a major byproduct of milk production, and circularity has been promoted through its concentration and inclusion in a variety of protein supplements for humans and livestock. Whey has also been used to produce bioplastics. Ricotta Cheese Exhausted Whey (RCWE), buttermilk, and ghee are additional milk byproducts targeted for enhanced circularity. Eggshells, composing shell, and membrane are the principal byproduct of egg production and are an excellent source of calcium for livestock and high-value proteins, respectively. Eggshells are also being used for bioremediation and as an ingredient in cement. Eggshell membranes are composed of structural proteins (i.e., collagen and keratins) as well as high-value proteins or peptides, such as lysozyme, ovotransferrin, ovalbumin, globulin, ovomucin, and defensin. Alternative uses for milk and egg byproducts continue to be explored as a means of further promoting circularity.

Zilio and Vasmara et al. (2025) describe how RCWE or "Scotta" from Ricotta cheese production can be converted from a byproduct to a bioproduct. RCWE is being used as feed for both ruminants and monogastrics, with a high lactose and mineral content. RCWE has also been proposed as a substrate for microbial fermentation to produce fatty acids and biogas. Production of microbial biomass and biogas enhance circularity through additional nutrient capture. Challenges in expanding the use of RCWE include variable composition, seasonal production, and a short shelf life. Overcoming these challenges could successfully transform RCWE from a waste product to a valuable resource.

Meza Ocampos et al. (2025) elaborate on the value of utilizing crop byproducts in the MERCOSUR/MERCOSUL regions of South America. These regions are among the largest producers of soybeans, corn, rice, wheat, coffee, and sugar in the world. Efforts are underway to optimize the utilization of byproducts from these crops within integrated crop–livestock systems. The circular bioeconomy is being supported through the training of highly qualified personnel and research infrastructure that supports biotechnology and process innovation. Land use policies are being developed that strike a balance between agricultural production, sustenance of biodiversity, and ecosystem management. Crop byproducts are often cost-effective, can be formulated into diets as a source of complementary nutrients to improve feed efficiency, while their use as feed prevents them from directly entering waste streams. Continued integration of crop byproducts into livestock production systems is a key step in the development of a circular bioeconomy in this globally important agricultural region.

Arsic et al. (2025a) outline the key role that livestock manure and postconsumer 'wastes' play in a circular bioeconomy. Livestock manures are managed with the aim to fertilize crops while preventing or limiting human, animal, and environmental health risks. Currently, manure is primarily used as a biofertilizer or for bioenergy production. As a fertilizer, manure aims to deliver carbon (organic matter) and nutrients to promote soil health and crop productivity. Manure is managed in a variety of manners and may be subject to secondary processing and the derivation of value-added end products such as biogas. In intensive livestock systems manure accumulation can result in undesirably high nutrient concentration within a limited geographical area. This is often a reflection of the increased transport costs associated with hauling manure longer distances from the source of production. Secondary processing such as stockpiling, composting, anaerobic digestion, and thermochemical processing can reduce manure volume and decrease transportation costs. Enhanced methods of nitrogen and phosphorus recovery from manure, such as nutrient stripping on farm, are being explored in an effort to increase the retention of these nutrients within agricultural systems. The authors emphasize the point that successful adoption of circular bioeconomy technologies that promote manure utilization requires coordinated action between technical, socioeconomic, policy, and regulatory stakeholders.

McAllister et al. (2025b) propose that circularity can contribute to the goal of achieving net-zero GHG emissions from agriculture. The threat of climate change has prompted many countries to aim for net-zero emissions, e.g., Canada has set a target of reaching net-zero by 2050. This goal demands strenuous response measures in many sectors, including agriculture, a prominent emitter of GHG in particular methane and nitrous oxide. Even with the employment of circularity principles, achieving the net-zero target by 2050 seems highly improbable, but it may serve a crucial role in motivating a fundamental restructuring and reorientation of farming practices, a transition that may also advance ecological and social goals. Examples of such restorative approaches include returning marginal lands to natural vegetation, developing multifunctional landscapes, perennializing farming, reestablishing animal-crop symbioses, resolving the nitrogen enigma, adopting holistic perspectives, and reimaging economic rewards. As for any mitigation scheme, aiming for net-zero involves marshaling the scientific understanding and infrastructure needed to measure reliably the ensuing progress. Such an approach will also inevitably involve identifying trade-offs across identified technologies. The tools to confidently predict the contribution of circularity and to verify if net-zero targets are reached are lacking. Despite its seemingly intractable challenges, the net-zero target may guide us toward living well on the land that must sustain us and those who follow.

In the final paper, Arsic et al. (2025b) describe the policy and regulatory impacts on livestock that influence the establishment of a circular bioeconomy. Circular economy and bioeconomy policies are often developed independently by most countries leading to contradictory conclusions and a lack of coherence across standards. The paper emphasizes the value of a One Health approach to assessing the contribution of livestock production systems to a circular bioeconomy. Currently, circular bioeconomy policies are lacking and are based on an amalgamation of circular economy and bioeconomy principles. Food and feed safety need to be paramount in the development of policy and regulatory frameworks that promote circularity. Planetary boundaries must also be respected in the development of circularity practices in livestock production. Hazard Analysis and Critical Control Points systems, to ensure byproducts enter the proper stream, whether it be food, feed, fertilizer, bioenergy, or waste, is essential to avoiding undesirable health or environmental outcomes.

This issue is relevant to livestock producers, supply chain partners (e.g., feed producers), farming organizations, processors, and retailers seeking to enhance the environmental performance of livestock production systems. Nonlivestock stakeholders can also benefit from insights into creating synergies within this sector through recycling and upcycling of residuals and waste. The collection will serve as a valuable tool for policymakers interested in fostering circular bioeconomy strategies for livestock supply chains.

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Acknowledgments

This manuscript is a product of the Livestock Environmental Assessment and Performance (LEAP) Partnership. The authors would like to thank members of the secretariat for their support: Xiangyu Song (Manager), Paolo Medei (Agriculture specialist), Edoardo de Santis (Partnership specialist), Julie Hanot, and Maud Lebeaupin (Interns). This manuscript was invited for submission by the World Association for Animal Production. The views expressed in this publication are those of the author(s) and do not necessarily reflect the views or policies of the World Association of Animal Production, the journal, the FAO or the publisher.

Author Contributions

Tim McAllister (Conceptualization, Writing—original draft), Barbara Renate Amon (Conceptualization, Writing—review & editing), Philippe Becquet (Conceptualization, Writing—review & editing), and Michael Lee (Conceptualization, Writing—review & editing)

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About the Authors

Tim A. McAllister received an M.Sc. in Animal Biochemistry from the University of Alberta in 1987 and a Ph.D. in Microbiology and Nutrition from the University of Guelph in 1991. He has worked as a research scientist with Agriculture and Agri-Food Canada since 1996, where he now holds the position of principal research scientist in microbiology and beef cattle production. His team has addressed a variety of topic areas related to optimizing the role of livestock in a circular bioeconomy. These include assessing and mitigating greenhouse gas emissions from agricultural systems, optimizing manure management, utilizing food loss and waste as feed, promoting food safety, and recognizing the role of grassland ecosystems in sustaining biodiversity. His team has been the recipient of numerous societal awards for their contribution to beef cattle production in North America.

Philippe Becquet is a consultant for regulatory and sustainability topics. He provides advice to the feed industry. Agronomist and animal nutritionist as background, Philippe Becquet has worked for more than forty years in the feed industry at various positions and in various companies, accumulating experience and expertise in livestock production systems and feed industry. He has also been active in feed industry associations such as IFIF (International Feed Industry Federation) and has contributed as an expert in the development of the Livestock Environmental Assessment and Performance (LEAP) guidelines on feed additives, the report on methane, and more recently to the report on the role of livestock in circular bioeconomy.

Barbara Amon is an Associate Professor for Environmental Engineering and Agricultural Engineering at the University of Zielona Góra, Poland, and board representative for research at the Leibniz Institute for Agricultural Engineering and Bioeconomy in Potsdam, Germany. Having had many years of practical, hands-on experience in agriculture alongside extensive research experience, she completed her habilitation in Agricultural Engineering at the University of Natural Resources and Life Sciences in Vienna in 2007. In addition to her research, she sits on many panels looking at sustainable agriculture, including the Intergovernmental Panel on Climate Change, UN Environment Programme, and the FAO LEAP partnership. She is also the Co-Chair of the Agriculture and Nature Panel as part of the UNECE Task Force on Emission Inventories and Projections and of the Expert Panel on Mitigation of Agricultural Nitrogen under the UNECE Task Force on Reactive Nitrogen.

Michael R.F. Lee is an expert in sustainable livestock systems, defining their role in securing global food security at the same time as protecting environmental health (Livestock's role in human and planetary health). He graduated with first-class honors in Animal Science from the University of Wales, Aberystwyth in 1997 and gained a PhD in ruminant nutrition (protein and energy metabolism) from the University of Aberdeen in 2001, followed by a Postgraduate certificate for teaching in higher education from Aberystwyth University in 2012. In November 2020, Michael moved from Rothamsted Research and the University of Bristol (where he held a joint position) to his current position as Deputy Vice Chancellor of Harper Adams University, England's Premier specialist agriculture and land use University. He has published over 375 research articles and papers, including articles in Nature and Science. He served as President of the British Society of Animal Science from 2018 to 2022 and was a Trustee of the society for 12 years. In August 2019, he was elected President of the European Federation of Animal Science Livestock Farming Systems Commission. He represents the UK on the Animal Task Force, a Public-Private think-tank informing the EU parliament in Brussels, and is co-chair of the UK Universities Climate Network—Net Zero group. In 2023, he was selected to join a Technical Advisory Group of the UN's Food and Agriculture Organization (FAO). Prof. Lee also sits on the BBC's Rural Affairs Committee, the Agriculture Advisory Group convened by the UK's Climate Change Committee (CCC), and the Scientific Council of the World Farmers Organization (WFO).