SPECIAL ISSUE: RAAN-A 2023 | McCLYMONT RURAL SCIENCE REVIEW
https://doi.org/10.1071/AN23061

CSIRO PUBLISHING

ANIMAL PRODUCTION SCIENCE

PERSPECTIVES ON ANIMAL BIOSCIENCES

The societal role of meat: the Dublin Declaration with an Australian perspective

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Handling Editor:
Frank Dunshea

Received: 7 February 2023
Accepted: 21 April 2023
Published: 29 May 2023

Cite this:
Pethick DW *et al.* (2023)
Animal Production Science, **63**(18), 1805–1826.
doi:10.1071/AN23061

ABSTRACT

It is clear that the societal role of meat is being challenged with ideological and simplified logic without substantiation from robust data-driven science. With this background, the international summit titled 'The societal role of meat – what the science says' was held in Dublin, Ireland, during October 2022, to provide evidence-based evaluations and the Dublin Declaration was signed by over 1000 scientists. In this paper, we provide a synopsis of the summit and then give context for evaluating the societal role of meat in Australia. The key themes of the summit were the essential roles of meat in (1) diet and health, (2) a sustainable environment and (3) society, economics and culture. Evidence clearly showed the role of meat as a nutrient-dense source of high-quality protein and micronutrients that can be safely consumed by humans. Further, the complementary role of livestock in agricultural systems was highlighted with both plant- and animal-based agriculture reliant on each other to maximise the efficient production of food. Thus, from both an Australian and world perspective, very little food considered to be human-edible is fed to livestock. The role of livestock in rural societies across the world was emphasised to underpin regional and national economies, with particular importance in those countries with developing economies to facilitate growing wealth to 'step out' of poverty and provide gender equality. Meat production, particularly from ruminants, is a critical part of Australian primary production and it is concluded that the Dublin Declaration is highly relevant to Australia. Finally, concern regarding future funding and organisation of research and extension is discussed. There is a need to continue funding highly collaborative programs that bring a broad range of disciplines together, in conjunction with undergraduate and postgraduate teaching to underpin the social license to operate for meat and livestock production.

Keywords: circularity, diet, livestock, meat, methane, nutrition, population health, sustainability.

Introduction

Advances in the nutritional sciences, agriculture, animal production and agronomy are based on quantification. The quantitative evaluation of evidence is the core strength of the scientific approach used by these disciplines and has been responsible for major gains in food production efficiency over the past century. However, public debate around complex societal challenges may at times be conducted without a strong quantitative base, often leading to suboptimal outcomes in understanding, legislation, and behaviour change. These concerns have been most prominent in Europe, but also other western countries, with calls from lobby groups and popular press to reduce meat consumption, especially from ruminants, to reduce global warming (BBC News 2022; Oreskes 2022; The Guardian 2022). Also, health professionals have stepped up the pressure to heavily reduce meat consumption with the recent Global Burden of Diseases (GBD 2019, Murray *et al.* 2020) study, substantially increasing the predicted burden (e.g. premature death or disability) attributable to red meat consumption between the 2017 and 2019 studies (Murray *et al.* 2020), a finding strongly challenged by a concerned group of scientists (Stanton *et al.* 2022). Scientific professionals with diverse backgrounds discussed these issues at recent forums of the International Congresses of Meat Science and Technology, where concern was raised that the debate around consumption of meat has been conducted with insufficient quantitative evaluation of the evidence and, hence, scientific rigour. Indeed, these same issues have been raised by eminent scientists over 30 years ago (Blaxter and Webster 1991). However, the view prevails, as articulated by Aiking (2014, p. 486S) 'Because animal protein production appropriates a huge and disproportionate share of natural resources, it presents a perfect target as an option for significant reduction.'. He goes onto suggest such reductions will also improve food security, equity, health, climate, and biodiversity. We believe that this is a simplistic solution to a series of complex societal issues, for the reasons discussed throughout the paper.

In October 2022, a meeting was convened in Dublin, Ireland titled 'The societal role of meat'. The meeting provided evidence-based evaluations of the societal role of meat and resulted in the Dublin Declaration (Box 1) signed by 1007 scientists as of 10 May 2023. Key themes of the conference were the roles of meat in (1) diet and health, (2) a sustainable environment and (3) society, economics and culture; a series of journal articles on these themes has been published in *Animal Frontiers* in 2023, plus the presentations are available at Teagasc (2023). In this paper, we provide a synopsis of the evidence presented at the conference and give an Australian context for evaluating the societal role of meat. Before tackling the primary objective of this paper, we address some of the shortcomings of GBD 2019. The commentary in our paper is not a review but a nuanced perspective on the false dichotomy between plant- and animal-sourced foods as they both have a role in a sustainable food supply (Comerford *et al.* 2021; Smith *et al.* 2022*a*).

Critique of the 2019 Global Burden of Diseases, Injuries, and Risk Factors study

In 2020, an otherwise highly respected research group from the University of Washington, with a 30-year history of contributions to global health metrics, published a questionable cohort study in *The Lancet* (Murray *et al.* 2020). This was an updated version of the usually highly regarded, standardised and comprehensive estimates of the Global Burden of Diseases, Injuries, and Risk Factors (GBD), which are used extensively by governments and non-government organisations to set policies and monitor progress over time in regard to policy targets. In the GBD 2019 publication (2019 estimates), Murray *et al.* (2020) diverged substantially from the previous 2017 estimates (Stanaway *et al.* 2018). The 2017 GBD analysis attributed 25 000 deaths to diets high in red meat (least important of 15 dietary factors). However, the GBD 2019 publication estimated diets high in red meat to be responsible for 896 000 deaths, an increase of 36-fold, making red meat the fifth leading dietary risk factor for mortality related to a range of chronic diseases (Stanton *et al.* 2022). One specific conclusion made by the group responsible for GBD 2019 was that the theoretical minimum risk exposure level for red meat was set at 0 g/day, indicating that risk started with even minimal intakes of red meat.

How could the two studies reach such conflicting conclusions? Previous GBD risk-factor analyses used data from published, peer-reviewed, systematic reviews and meta-analyses but the GBD 2019 Risk Factors Collaborators did not identify which peer-reviewed publications were used in their updated conclusions, instead stating there was 'sufficient evidence supporting the causal relationship of red meat intake with ischaemic heart disease, breast cancer, haemorrhagic stroke, and ischaemic stroke' (Murray *et al.* 2020, supplementary material p. S283) and added these outcomes to previously identified relationships with diabetes and colon cancer.

However, this is not in agreement with other recently conducted systematic reviews and meta-analyses (Stanton *et al.* 2022). In a meta-analysis of cohort studies by Zeraatkar *et al.* (2019), it was found that there was low- to very low-certainty evidence that diets higher in unprocessed red meat may result in risk of cardiovascular disease, stroke, myocardial infarction, type 2 diabetes, and overall lifetime cancer mortality.

This lack of quantitative evaluation and rigour in science in GBD 2019 was highlighted in presentations at the Dublin summit from Alice Stanton and Bradley Johnston (Johnston *et al.* 2023), who stressed the need for rigorous approaches to meta-analytical data. The lack of appropriate methods to pooling of data in GBD 2019 represents a failure of editorial method. Stanton *et al.* (2022) noted the lack of adherence in the article to the basic tenants of quantitative analysis, including a failure to utilise Guidelines for Accurate and Transparent Health Estimates, and the failure to use Preferred Reporting Items for Systematic reviews and Meta-Analyses (Moher *et al.* 2009).

The result of these failures and others highlighted by Stanton *et al.* (2022) led those authors to conclude that 'it would be highly inappropriate and imprudent for the GBD 2019 dietary risk estimates to be used in any national or international policy documents, nor in any regulatory nor legislative decisions'. The most important lesson from the problems with GBD 2019 is that rigorous reviewing standards must be applied to all papers submitted. While meta-analysis of randomised controlled trials is the strongest form of evidence, meta-analysis of observational studies, such as many of those contributing to GBD 2019, is not as robust and must be subject to careful scrutiny.

In addition to inappropriate analysis, undue reliance was placed on dietary studies of western developed countries being representative of humanity in general. When anthropological investigation of human dietary habits and food reliance are conducted across multiple societies, including many in developing countries, the results show a vastly different picture of meat consumption and life expectancy, child development and overall health. A recent analysis of life expectancy across 175 societies, including many in developing countries

Box 1. Dublin Declaration

The Dublin Declaration of scientists on the societal role of livestock

Purpose of this declaration

Livestock systems must progress on the basis of the highest scientific standards. They are too precious to society to become the victim of simplification, reductionism or zealotry. These systems must continue to be embedded in and have broad approval of society. For that, scientists are asked to provide reliable evidence of their nutrition and health benefits, environmental sustainability, socio-cultural and economic values, as well as for solutions for the many improvements that are needed. This declaration aims to give voice to the many scientists around the world who research diligently, honestly and successfully in the various disciplines in order to achieve a balanced view of the future of animal agriculture.

Challenges for livestock

Today's food systems face an unprecedented double challenge. There is a call to increase the availability of livestock derived foods (meat, dairy, eggs) to help satisfy the unmet nutritional needs of an estimated three billion people, for whom nutrient deficiencies contribute to stunting, wasting, anaemia, and other forms of malnutrition. At the same time, some methods and scale of animal production systems present challenges with regards to biodiversity, climate change and nutrient flows, as well as animal health and welfare within a broad One Health approach. With strong population growth concentrated largely among socioeconomically vulnerable and urban populations in the world, and where much of the populace depends on livestock for livelihoods, supply and sustainability challenges grow exponentially and advancing evidence-based solutions becomes ever more urgent.

Livestock and human health

Livestock-derived foods provide a variety of essential nutrients and other health-promoting compounds, many of which are lacking in diets globally, even among those populations with higher incomes. Well-resourced individuals may be able to achieve adequate diets while heavily restricting meat, dairy and eggs. However, this approach should not be recommended for general populations, particularly not those with elevated needs, such as young children and adolescents, pregnant and lactating women, women of reproductive age, older adults, and the chronically ill. The highest standards of bio-evolutionary, anthropological, physiological, and epidemiological evidence underscore that the regular consumption of meat, dairy and eggs, as part of a well-balanced diet is advantageous for human beings.

Livestock and the environment

Farmed and herded animals are irreplaceable for maintaining a circular flow of materials in agriculture, by recycling in various ways the large amounts of inedible biomass that are generated as by-products during the production of foods for the human diet. Livestock are optimally positioned to convert these materials back into the natural cycle and simultaneously produce high-quality food. Ruminants in particular are also capable of valorising marginal lands that are not suitable for direct human food production. Furthermore, well-managed livestock systems applying agro-ecological principles can generate many other benefits, including carbon sequestration, improved soil health, biodiversity, watershed protection and the provision of important ecosystem services. While the livestock sector faces several important challenges regarding natural resources utilisation and climate change that require action, one-size-fits-all agendas, such as drastic reductions of livestock numbers, could actually incur environmental problems on a large scale.

Livestock and socio-economics

For millennia, livestock farming has provided humankind with food, clothing, power, manure, employment and income as well as assets, collateral, insurance and social status. Livestock-derived foods are the most readily available source of high quality proteins and several essential nutrients for the global consumer. Livestock ownership is also the most frequent form of private ownership of assets in the world and forms the basis of rural community financial capital. In some communities, livestock is one of the few assets that women can own, and is an entry point towards gender equality. Advances in animal sciences and related technologies are currently improving livestock performance along all above mentioned dimensions of health, environment and socio-economics faster than at any time in history.

Outlook for livestock*

Human civilisation has been built on livestock from initiating the bronze-age more than 5000 years ago towards being the bedrock of food security for modern societies today. Livestock is the millennial-long-proven method to create healthy nutrition and secure livelihoods, a wisdom deeply embedded in cultural values everywhere. Sustainable livestock will also provide solutions for the additional challenge of today, to stay within the safe operating zone of planet Earth's boundaries, the only Earth we have.

For scientific evidence please refer to presentation recordings from the 19/20 October 2022 International Summit on the Societal Role of Meat. Evidence has also been published in a Special Issue of *Animal Frontiers*, volume 13, issue 2, April 2023.

* The wording of this paragraph is from the Solution Cluster on Sustainable Livestock at the UN Food System Summit 2021.

where food supply and breadth is limited, showed a positive correlation between meat consumption and life expectancy (You *et al.* 2022).

The GBD 2019 Risk Factors Collaborators also ignored the additional deaths and illness from iron-deficiency anaemia, sarcopenia, and child and maternal malnutrition that would result from zero red meat intake, particularly in developing countries where red meat is a critical aspect of non-diverse and marginal diets.

Of great concern to both human health and the meat industry is the international impact that this misinformation is having. Since publication, GBD 2019 (Murray *et al.* 2020) has been cited by at least 635 documents, including 351 scientific papers and nine policy documents. The extensive quoting of GBD 2019 risk-factor data in the evidence document of the UK's National Food Strategy (Stanton *et al.* 2022) is a significant example of the potential negative impact of misinformation.

Dublin Declaration conference themes

Further details and evidence for the following summaries of the conference themes are available from published conference publications in *Animal Frontiers*, volume 13, issue 2, 2023. The themes are similar to those examined by Leroy *et al.* (2022).

The role of meat in diet and health

The first of the evidence-based themes for the Dublin Conference focussed on the role of meat in the diet and health and opened with a talk on the evolution of hominins and the close association with meat eating (Leroy *et al.* 2023). The introduction of meat eating was initially via scavenging, then hunting and finally by animal domestication. The idea that meat consumption is detrimental to health is at odds with the long history of human and prehuman hominin reliance on animal-sourced food (Mann 2018).

There are numerous highly published fields of investigation used by anthropologists to deduce the evolutionary diet of our evolving hominin ancestors, and they include the following: (1) changes in cranio-dental features; (2) fossil isotopic chemical tracer methods; (3) comparative gut morphology of modern humans and other mammals; (4) the energetic requirements of developing a large ratio of brain to body size; (5) optimal foraging theory; (6) dietary patterns of surviving hunter-gatherer societies; (7) specific diet-related adaptations; (8) fossil evidence of animal butchery (Mann 2000, 2018) and; (9) coevolution of mammalian hosts and their various parasites. Cestodes of the family Taeniidae, for example, are parasites of carnivores, spread by eating meat (Henneberg *et al.* 1998).

The study of dietary patterns of surviving hunter-gatherer societies also gives us a clear picture of what our pre-agricultural ancestors consumed (Mann 2018), showing that the majority of such societies obtained between 56% and 65% of their subsistence (dietary energy) from animal-sourced foods (Cordain *et al.* 2000). Palaeobiological studies of the transition from gatherer-hunter-fisher diets to agriculture subsistence have shown nutritional deficiencies, infection, and metabolic perturbations associated with reduced meat consumption and dietary diversity (Chinique de Armas and Pestle 2018).

Essential nutrients and nutrient availability

Humans exhibit a range of specific adaptations demonstrating extensive reliance on animal-sourced foods in the diet (Mann 2018). These include (1) an inefficient ability to elongate plant-rich 18 carbon omega-3 fatty acids into the 20- and 22-carbon polyunsaturated fatty acids (PUFA; Emken *et al.* 1992), required for structural and functional purposes in humans, (2) decreased ability to synthesise the amino sulfonic acid taurine (found only in animal tissue; Chesney *et al.* 1998), and (3) haem iron-rich compounds derived only from animal foods are absorbed by humans in preference to ionic forms of iron common in plants. Herbivorous animals cannot absorb these haem complexes and rely on absorption of the ionic form of iron (Bothwell and Charlton 1982).

From a broader perspective, meat is a critical source of high-quality protein and indispensable amino acids (IAA). It is essential to consider not only the amino acid content, but also digestibility of the indispensable amino acids in a food (Leroy *et al.* 2023). For meat, the digestible indispensable amino acid score (DIAAS; Moughan 2021) is in the range of 0.8–1.4, whereas values for most traditional plant proteins are markedly lower due to limiting IAA or reduced availability (Marinangeli and House 2017). Moughan (2021) showed that more than 100 countries faced inadequate protein supply for their populations after consideration of bioavailability. These were predominantly lower-income countries, and the poorer bioavailability was attributed to low dietary diversity, including minimal access to animal-sourced foods (Leroy *et al.* 2023).

There are also several key micronutrients of importance for health, and in particular for human brain development, structure and function. These include iron, zinc, vitamin B_{12} and long-chain omega-3 fatty acids. If not supplemented, these nutrients are either obtained exclusively from animal-sourced foods or are more bioavailable in those foods. It is phytate, the storage form of phosphorus in plants, that binds and reduces the availability of minerals, amino acids and energy; this is well established in monogastric nutrition (Selle *et al.* 2000; Bryden *et al.* 2007). Moreover, there is human evidence that plant-based diets decrease bone health (Ma *et al.* 2021; Falchetti *et al.* 2022) and increase the incidence of depression (Lee *et al.* 2021; Jain *et al.* 2022). In addition, meat contains a range of other B vitamins that can be limiting in micronutrient-poor diets, including thiamine and niacin (Leroy *et al.* 2023).

The importance of meat in the supply of critical nutrients was reinforced through a presentation on the modelling of the global food system (Smith *et al.* 2022*b*). The modelling highlights the value of bioavailability of protein, specific amino acids, iron and zinc, when evaluating the potential to deliver essential nutrients to meet the growing demand for food through to 2050. Smith concluded that meat supply is critical to the delivery of micronutrients to provide adequate diets for humans on a global basis (Leroy *et al.* 2023).

The role of meat in a sustainable environment

Deeper understanding of the interactions among livestock, the environment and climate are a pre-requisite to achieving sustainable farming and food-production systems. Valuable perspectives on the interactions among livestock, the environment and climate were presented at the meeting. The contribution of pastoral management of ecosystems was explored and the integration with, and importance to society was highlighted. Manzano *et al.* (2021) estimated that 60% of the terrestrial mass is used by the pastoral industries in over 100 countries. These 'open ecosystems' have developed over the past 15 million years in association with extinct megafauna. The current Bovidae are an example of megafauna and are prevalent in these open ecosystems and with current management may have a methane output similar to that before European settlement in North America (Hristov 2012).

Some parts of the world are very dependent on pastoral systems for wellbeing and economy; for example, 88% of agricultural GDP in Mongolia and 60% in Kenya depend on pastoral systems. Manzano *et al.* (2021) and Leroy *et al.* (2022) argued for greater recognition of the complexity of evaluating food production systems and for transdisciplinary approaches to address the suitability and societal value of pastoral systems, while supporting the environmental sustainability of the systems.

A consistent theme that emerged from the presentations of Manzano and Rowntree at the Dublin Conference was the need to ensure that the correct metrics are used to evaluate the sustainability of environmental impacts of pastoral systems and animal production (Manzano *et al.* 2023; see Box 2). For example, the continued use of global warming potential (GWP100) metric where methane has 27–30 times the warming potential of carbon dioxide over 100 years needs to be balanced against GWP*, which recognises that methane has a short half-life of about 12 years. The GWP100 metric overestimates the warming potential of methane when methane emissions are stable or falling and underestimates warming when methane emissions are increasing (Place *et al.* 2022). Utilisation of the non-human edible biomass by ruminants grazing pastoral systems transforms the biomass into edible human protein and micro-nutrients. This theme was reinforced in the presentation by Wilhelm Windisch who explored the role of grasslands and nutrient circularity in animal agriculture. In central Europe, each kilogram of plant-based food has been estimated to be associated with at least 3–4 kg of non-human edible biomass from best-practice agriculture. Globally, the relative amounts of non-human edible biomass are far higher (Windisch 2021; Thompson *et al.* 2023). This is important when considering the environmental impacts of plant- and animal-sourced foods. Further, Windisch (2021) and Smith *et al.* (2022*a*) noted that that there is little competition between plant-based and animal-based production and argue that they are complementary. It is critical to evaluate the efficiency of livestock production in terms of production of bioavailable essential nutrients for humans. Use of this metric will highlight the limitations of a singular reliance on plant-based diets and the value of meat in the diet.

The role of meat in society, economics and culture

Often meat is considered only as part of the diet and yet it has a much more diverse role (CAST 1999). Whether in an African village or a small town in rural Australia, livestock production can significantly affect economic prosperity. In developing communities, the productivity of local livestock also has implications for health and education.

The crucial role of meat in developing societies

In examining how global nutrient supplies from food match up to global population requirements, it is evident that meat contributes the majority of the global vitamin B_{12} supply (DELTA Model®), as well as a quarter of vitamin A (in retinol equivalents), and high proportions of other B vitamins and several minerals such as iron and zinc, despite meat making up only 7% of global food mass and 11% of global food energy, providing further evidence for its nutrient density (Smith *et al.* 2022*b*). Importantly, this global picture does not capture regional variation. In the case of unprocessed red meat, the average per capita daily consumption is estimated at just 7 g in southern Asia, 24 g in Sub-Saharan Africa, 36 g in the Middle East and 45 g in northern Africa. Values are much higher in high-income countries, 51 g globally, 68 g in Latin America and the Caribbean, 87 g in Southeast and eastern Asia, and a sizable 114 g in central or eastern Europe and central Asia (Miller *et al.* 2022). Regions with the lowest intake also show the highest prevalence of malnutrition (Adesogan *et al.* 2020; Leroy *et al.* 2023). For instance, resource-poor countries suffer from a high prevalence of juvenile stunting and other forms of malnutrition, in part due to inadequate dietary diversity and a heavy reliance on a single staple (typically cereal grains) for daily energy needs (Ranum *et al.* 2014; Leroy *et al.* 2023).

In many countries of Sub-Saharan Africa and southern Asia where meat intake is very low, and malnutrition is high, animal husbandry is a critical aspect of economic survival as well as nutritional necessity, particularly for the young. These populations could benefit from an increased rather

Box 2. Definitions

Definitions and efficiency metrics for animal production

Sustainability: an attribute of a management strategy for a defined area or region. The parameters defining the outcomes of the strategy must be measurable and time bound, with an emphasis on longer time frames (decades or greater). Inherently, a sustainable strategy must address maintenance of productive function, economic viability, biodiversity including phylogenetic diversity, ecosystem function, social acceptability.

Arable: land that is fit for the purpose of growing crops.

Biogenic gas: a gas critical for and produced by living organisms.

Concentrates: feeds lower in fibre, especially fibre >0.5 cm and include grains, by-products of flour and ethanol production, protein meals, pulses and whole cottonseed.

Global warming potential (GWP100): means of quantifying the strength of different green-house gases (GHG) relative to carbon dioxide. It is derived from estimating the total change in atmospheric energy balance resulting from a pulse emission of the gas, relative to CO_2, over a specified time frame (typically 100 years). Methane (CH_4) is estimated to have a GWP100 of 27–30.

GWP*: a metric developed to better reflect the effect of short-lived climate pollutants (SLCP). For GWP*, the time-integral of the rate of change of SLCP emissions over any given time period, or, equivalently, the change in SLCP emission rates between the beginning and end of that period, multiplied by GWPH (H = time period), gives total CO_2-e* emissions over that period.

Greenhouse gas (GHG): a gas that can capture and retain heat from sunlight, thus warming the atmosphere.

Maintenance: the energetic costs of metabolic service and repair functions that keep an animal alive without retaining energy or being productive.

Metabolisable energy: energy (ME) obtained from the diet able to be utilised by the animal for maintenance and production; the application of ME implicitly considers losses in production of net energy. The ME accounts for gaseous energy losses in utilisation of digestible energy.

Efficiency measures

Gross emissions: total emissions produced.

Net emissions: emissions produced minus carbon fixed over a defined life-cycle.

Life-cycle analysis: accounts for all emissions produced and fixed from production to consumption.

Intensity of production (GHG or methane): amount of livestock product produced (kg live weight, meat or milk) per unit of GHG or methane.

* Efficiency of production on human-edible intake basis: metabolisable energy for human consumption divided by gross energy consumed of human edible food (J per J).

*Net protein contribution of meat production: efficiency for converting the human-edible portion of the diet into human-edible protein (meat) × (digestible indispensable amino acid score for meat/digestible indispensable amino acid score of the diet). A score of >1 means more human-edible protein produced than consumed.

*The latter measures can be extended to all essential nutrients produced and consumed.

https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

Water definitions

Blue water: the water found in rivers, lakes, dams, and aquifers. Blue water is used for irrigation and for industrial and domestic use.

Green water: the water available in the soil for plant growth and equal to the volume of water lost through evapotranspiration.

Grey water: water that has been previously used and may contain impurities, including leached nutrients and pesticides following agricultural use. Grey water is usually reused, especially during droughts.

Virtual water: the volume of water used to make a product and is the sum of the water use throughout the production chain, not just the water in the product. It may contain green, blue, and grey water.

than reduced meat intake (Randolph *et al.* 2007; Adesogan *et al.* 2020). A prominent feature of this session was the role of meat as a dietary ingredient for children, pregnant and lactating women, women of reproductive age, older adults, and individuals in low- and middle-income countries (Leroy *et al.* 2023). Animal-sourced foods, such as meat, are the best source of nutrient-rich foods for children in their first 1000 days (a finding supported by the World Health Organization), leading to normal growth and development and compelling benefits on cognitive functions (Balehegn *et al.* 2022). Thus, global efforts to moderate meat intake for environmental or other reasons should be careful not to restrict its growth in populations where consumption is already low, as this could hinder progress towards reducing malnutrition and thereby not address human suffering and the stifling of economic development (Wong *et al.* 2017; Balehegn *et al.* 2019).

In many regions where there is a lack of animal-sourced food in the diet, the population is also exposed to mycotoxins in their food staples (especially maize and peanuts). Chronic exposure to mycotoxins in developing societies have been shown to significantly affect public health by reducing infant growth and development, causing immunosuppression, and increasing the risk of cancer, especially hepatocellular carcinoma (Wu *et al.* 2014; Wild *et al.* 2015; Bryden 2019). Reduced access to animal-sourced foods in these societies will further decrease public health as facilities for food storage are often rudimentary, facilitating fungal growth and mycotoxin production in stored grains. Moreover, in developed countries there is increasing pressure to shift from red meat to plant–based meat analogues. This neglects natural toxin contamination, especially by mycotoxins of these plant products (Mihalache *et al.* 2022*a*), as has also been found in plant-based milks (Arroyo-Manzanares *et al.* 2019) Although reducing meat consumption does decrease some diet-related health risks, the overall risk to health is increased by the consumption of plant-based meat substitutes (Mihalache *et al.* 2022*b*). In other surveys, it has been also found that populations that exclude animal-sourced foods from their diets have greater exposure to mycotoxins (Leblanc *et al.* 2005; Penczynski *et al.* 2022).

Livestock in countries with developing and emerging economies

The crucial role of livestock in Africa was outlined by Shirley Tarawali from the International Livestock Research Institute (Baltenweck *et al.* 2020; Tarawali 2022; Ederer *et al.* 2023). Some 23% of the world's cattle are in Africa, supplying about 8% of the world's meat, contrasting this to the USA and Europe where cattle populations total 6–7%, yet supply 15–18% of the world's meat, clearly showing the low productivity of the African livestock systems. More broadly, in low- to middle-income countries, 1.7 billion people derive some livelihood from livestock and poultry and over half a billion depend on livestock and poultry. Improving livestock productivity and health in these countries is crucial for sustaining incomes, reducing financial risk, growing wealth to 'step out' of poverty, gender equality and of course adequate nutrition (Alders and Pym 2009; Wong *et al.* 2017; de Bruyn *et al.* 2020). It was concluded that a concerted global effort was needed to support livestock productivity (and so reduce methane intensity) in low- to middle-income countries to improve the standards of living.

In vitro meat and meat substitutes

The potential for *in vitro* or cultured meat production was examined by Paul Wood (Wood *et al.* 2023). The overall process is to culture muscle cells in bioreactors in highly controlled and sterile conditions similar to those used for growing microbes to produce medical and other products (Bonny *et al.* 2017; Ellies-Oury *et al.* 2022). It was concluded that the technology was well established and that cultured meat will appear on the market for consumers. Various private investors have claimed that the cultured-meat scenario will have benefits over livestock, citing lower carbon footprints and environmental damage, plus improved animal welfare due to less animal killing. However, the conclusion was that the technology will never be able to scale at the commodity level to represent a real alternative to traditionally raised meat. Moreover, it will never be a solution to providing high-quality nutrition in low- to middle-income countries.

Similar arguments apply to plant proteins processed to resemble animal-based foods and also referred to as meat substitutes, meat analogues, fake meat, and mock meat (Boukid 2021). It is worth noting that the environmental footprint of plant-based meat substitutes determined from life-cycle analyses may be lower than that of feedlot beef, but higher than that of beef produced on pasture (van Vliet *et al.* 2020).

World food flows

Global world food flows were examined by Peer Ederer from GOAL Sciences who have developed a modelling platform called 'Planet Food System Explorer' (Ederer *et al.* 2023; GOAL Sciences 2023). The modelling conclusively shows that, on a global basis, both the cost and supply of calories for humans is theoretically enough to meet world demand if there were equitable distribution. However, the supply of bioavailable protein and nutrient-rich foods is more precarious, with over a third of the world population being unable to afford these nutrients. Animal-sourced foods, especially dairy, poultry and eggs, are very cost-competitive on a world stage. Indeed, the cost of bioavailable, high-quality protein from poultry and eggs is cheaper than the same nutrients derived from cereals, meaning that, from a bioavailable-protein perspective, it is better to feed cereals to chickens than to humans! It was also argued that increasing alternate protein supplies especially from grain legumes has proved problematic due to agronomic difficulties in many climatic and geological scenarios, along with the issue of anti-nutritional compounds that legumes contain. In addition, the view that livestock feed grain competes for human food was shown to be flawed, with, for example, only 5% of the world ruminant diet consisting of grains and 86% of the world livestock being fed non-human-edible products (Mottet *et al.* 2017; Leroy *et al.* 2022; Ederer *et al.* 2023). A troubling trend for competition between animal feed versus petroleum production was also highlighted, adding further constraints on world protein production. Finally, it was concluded by Ederer *et al.* (2023) that depending on what value is chosen for the average protein requirement per person per day, the world protein supply (from all sources) is either adequate, or needs to expand by up to 80%. If this is projected out to 2050, on the basis of population growth estimates, then global protein supply needs to increase by 20–150% over the current levels. These analyses have highlighted the important role of food production from both animals and crops (Ederer *et al.* 2023).

Ethics of livestock and meat production

The ethics of meat consumption were examined by Candace Croney who asked the following question: 'Is eating meat morally defensible?' (Croney and Swanson 2023). While the strength of the scientific argument was based on increased global food demand, historical and cultural prominence, nutritional benefits, increased demand in developing and emerging economies and technological developments that distribute benefits, Croney also discussed the perspective that there can be arguments against meat consumption. Ethics questions are more likely to emerge when science is equivocal and ethics questions are more prevalent when there is affluence and choice; however, 'public opinion' is diverse. In other words, distinct differences exist among consumer populations and their perceptions and needs. For affluent countries, food is more than sustenance and reflects values and social justice, with many responding to advocacy groups and others seeking to reduce meat consumption (McKendree *et al.* 2014). Arguments that meat eating does harm include animal suffering and death, has negative impacts on natural resources, ecosystems and local communities, and aspects of worker health and safety and quality of life. However, these arguments have often been unduly simplified, ignored important stakeholders and have poorly framed arguments (de Bruyn *et al.* 2020; Thompson *et al.* 2023). Indeed, as discussed by Leroy *et al.* (2022), crop production, the basis of a diet that excludes animal products, comes with an animal death toll that may be even higher than that from large-animal husbandry and slaughter. There are strong positive arguments for the environmental sustainability of meat production and the application of the least harm principal (Regan 1983; Davis 2003) indicates that animal welfare will be best served by inclusion of meat from large herbivores in the diet, rather than having diets that exclude animal products. In terms of equitable access to food, many do not have the luxury of choice and should have access to meat, as malnutrition is still prevalent among children and females when access to high-quality proteins and micronutrients is limited. The latter theme was explored in depth at the meeting. Croney and Swanson (2023) concluded that eating meat was morally defensible, as have others (de Bruyn *et al.* 2020).

Societal role of livestock and meat in Australia

Australia has a large land area predominantly suitable for extensive ruminant production but a relatively small population, thus a high proportion of ruminant products are exported. In addition, to the beef, sheep and dairy industries, Australia has very efficient pig and poultry production that includes the pig meat, chicken meat and egg industries. These non-ruminant industries largely cater for the domestic market and have been included in this section to reflect the meat-intake pattern of Australian consumers.

Australian agriculture

Approximately 55% of Australia's land mass is used for agriculture (325 million ha), of this, approximately 283 million ha, or more than 85%, is native vegetation used for grazing, another 35–41 million ha is improved pasture and only 21–31 million ha is used for crops in any one year (Australian Bureau of Statistics 2016–2017; Australian Bureau of Agricultural and Resource Economics and Sciences 2022*a*); this reflects the scarcity of arable land in Australia (Fig. 1). The area dominance of grazing native vegetation reflects the importance of the pastoral grazing systems in northern Australia. About 60% of Australia's beef cattle is in the northern tropics and subtropics. Large areas of land in this region are not suitable for arable agriculture, and thus livestock industries based on the grazing of native pastures remain the only, or one of very few, financially viable industries in these areas. A similar assessment can be made of the southern rangelands.

Although much smaller in size, the mixed farming zone is a key driver of food production in Australia. The agro-climatic regions supporting mixed farming range from the winter-rainfall Mediterranean and temperate climates of south-western Western Australia and southern South Australia into the wet temperate regions in Victoria, Tasmania and New South Wales, then up through to the subtropics in southern and central Queensland (Bell *et al.* 2019; Fig. 1). The zone produces most of Australia's crops and 40% of the livestock; approximately 83% of the cropping farms include livestock (Bell *et al.* 2014, 2019).

Meat in the Australian diet

The role of meat in diet and health in Australia is similar to that described earlier for other countries and populations. Australians are among the highest meat eaters in the world, with meat consumption at more than 100 kg per capita for each of the past 60 years (Wong *et al.* 2015; Whitnall and Pitts 2020). However, overtime, the relative importance of different meats has changed. Beef dominated intake until about 15 years ago and now chicken meat (47.2%) dominates Australian consumption, followed by pork (28.4%), beef and veal (18.9%) and lamb (5.5%) (Australian Bureau of Agricultural and Resource Economics and Sciences 2022*a*). Australians do have access to a series of books based on the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Total Wellbeing Diet (Noakes and Clifton 2005, 2006). The books, written for Australians, are targeted at consumption of a healthy diet to facilitate weight loss and allow for a moderately high level of animal protein intake (Noakes *et al.* 2005). The diet is also based on a high intake of fruit and vegetables, low in saturated fat and

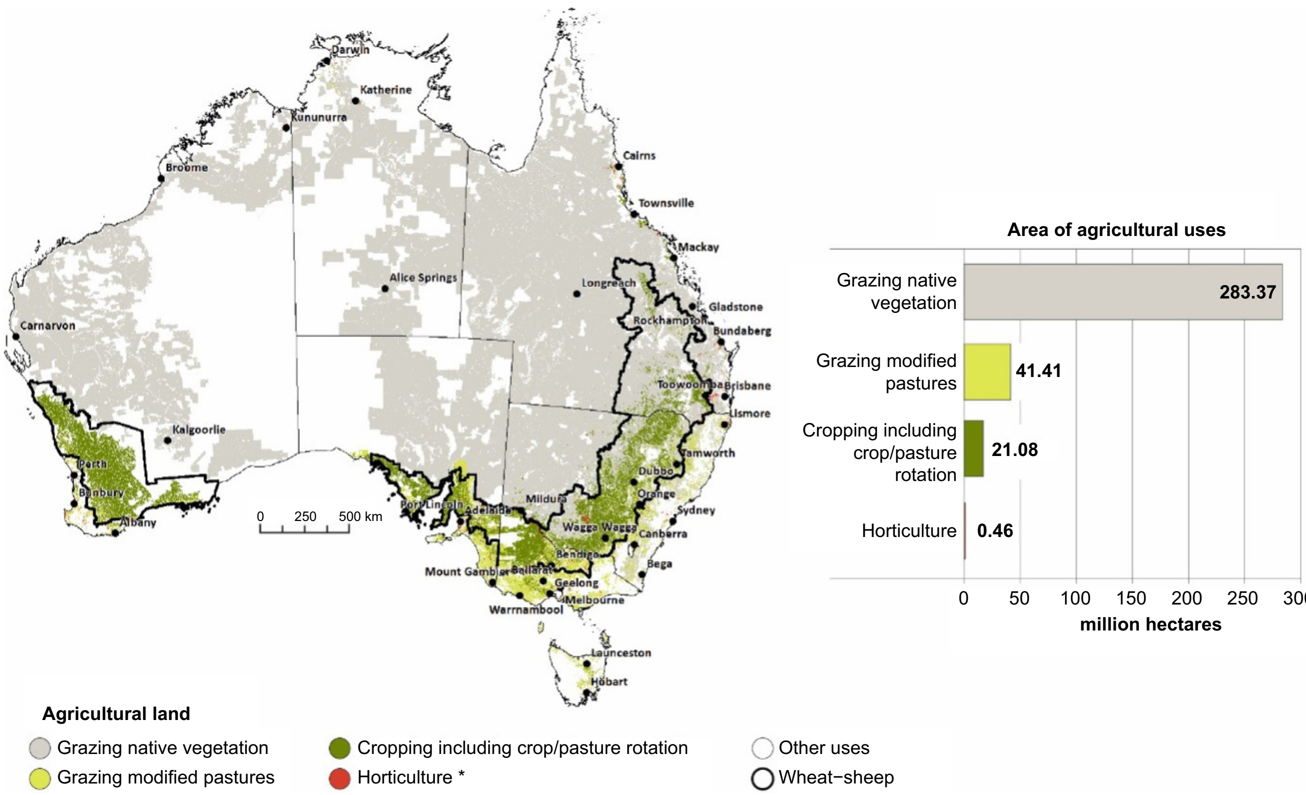

Fig. 1. Areas of agricultural use in Australia as extracted from Snapshot of Australian Agriculture (Australian Bureau of Agricultural and Resource Economics and Sciences 2022*a*).

alcohol and encourages moderate physical activity (Noakes and Clifton 2008). The Level 1 plan suggests 200 g of red meat four times weekly, which is within the Australian Guide to Healthy Eating (NHMRC 2013).

The importance of meat in the Australian diet has been long recognised (Baghurst 1999; Nutrition and Dietetics 2007). The special issue of Nutrition and Dietetics (2007), commissioned by Meat and Livestock Australia contained 20 papers by leading Australian nutrition academics and scientists and covered the nutrient content of meat, the role of red meat in nutrition, in diets at different life stages, and management of chronic disease. As stated in the special issue, the conclusions to the role of red meat in healthy Australian diets' 'concur with nutrition statements from the National Heart Foundation of Australia, and have the support of the Dieticians Association of Australia as a useful summary of the contribution of red meat to healthy eating.'

Animal-sourced food and efficiency of production

Costa (2007) and Bell *et al.* (2011*a*) provided concise reviews of the challenges and opportunities facing meat production by the Australian livestock industries. Australia is a significant supplier of food, particularly animal protein, to the world. Australia is the fourth largest beef exporter and the world's largest exporter of sheep and goat meat (Meat & Livestock Australia 2022); beef exports represent 14% of the world market. Of total beef and veal, lamb and mutton produced, 78% is exported to over 100 countries, emerging, developing and developed. The dominant market for beef is Asia, with Japan, South Korea and China being the largest markets. Indonesia was Australia's largest market for live cattle exports in 2021 (52%), followed by Vietnam (22%) and China (13%). More than 700 000 head of cattle were exported alive in 2021. For sheep meat, the highest sales were to China (30%), followed by the United States (23%) and Malaysia (6%). Live sheep exports in 2019 were more than 550 000, with Kuwait (60%) as the primary destination (Meat & Livestock Australia 2022). These exports both as meat and live animals represents a critical contribution to the intake of high-quality protein and other essential nutrients (particularly essential fats, vitamins and minerals) in many parts of the world. Part of the reason for Australia's success in growing and exporting meat is efficient systems for conversion of plants to products.

Cattle in the pastoral zone

Most of Australia's cattle are grazed in the rangelands of the monsoonal north, part of the 85% of agricultural land where rainfall is usually too low or erratic to support crops or allows only limited pasture improvement. Without livestock, this zone would produce little or no food at all and the plant resources growing there would not contribute to feeding people inside and outside of the country. The value of grazing is best demonstrated through calculation of net protein contribution (NPC) for a grazing system (Box 2). NPC represents the amount of human-edible protein produced, divided by the amount of human-edible protein consumed by the animal (both produced and consumed, adjusted for amino acid value). In a grazing system that uses a small amount of human-edible protein for feed supplements, an NPC of 1597 has been calculated, that is, 1597 kg human-edible protein produced for every kilogram consumed (Thomas *et al.* 2021*a*). It is not a choice between animal and plant protein production, but between animal protein and no protein/food production at all.

In northern Australia, the quality of native pastures is usually low. High rainfall and leaching keep essential nutrients, especially nitrogen, low in the soil profile, and plants are, therefore, usually low in protein. Due to its fragile environment, it has been recognised for many years that it is an area that must be carefully managed (Ferguson 1973). The wet, monsoonal-zone native pastures have high levels of structural carbohydrates, high cellulose and lignin contents, and low digestibility (Minson 1990; Charmley *et al.* 2023), making it difficult for livestock to obtain sufficient energy for rapid growth. Many of the soils of northern Australia are low in phosphorus, and the plants usually have also low phosphorus content and phosphorus deficiency of cattle is prevalent without supplementation (Dixon *et al.* 2017; Schatz *et al.* 2023). Less than 5% of the pastures in these regions have been improved with fertilisers and introduced pasture species. Expenditure on fertiliser for large and medium beef properties in northern Australia has been low to negligible (Lean *et al.* 2011). The advantages of the extensive pastoral system are the low cost of pasture, while the disadvantage is the great variability in pasture production reflected in a marked variation in growth and development of animals.

The northern pastoral zone is characterised by low-cost pasture and cyclic forage variability. The major constraints to production are under-nutrition, both in amount and quality of feed, costs of management inherent to such extensive properties, and heat stress and parasites and disease (Bell and Sangster 2023). Poppi and McLennan (1995) reviewed major limitations to the beef production system arising from deficiencies in the energy and protein content within the dominant pastures of the northern beef industry and explored the interactions among these major nutrients. These limitations are often expressed in poor reproductive efficiency (see McGowan *et al.* (2014); this report has since been published in 2023 in a series of papers in *Animal Production Science* **63** issue 4).

Cyclic weight gain and loss that reflects the annual change in pasture quality and quantity, resulting in a low efficiency of production, is a characteristic of the system. However, Lean *et al.* (2011) reviewed 40 years of published weight-gain data from northern Australia and identified substantial variations (>1 kg/day difference) in the performance of the cattle on native pastures and further identified substantial (>70% improved weight gain) responses in some cases to supplementation. Bell and Sangster (2023) reviewed the substantial benefits from use of improved agronomic approaches to increase weight gains, including increased adoption and management of *Stylosanthes* species, *Leucaena*, *Desmanthus* cv and other tropically adapted legumes. These findings indicate the potential for the northern beef system to be more productive.

Stocking rates are often extremely low in the pastoral zone, with many hectares being allocated to a single animal (Tothill and Gillies 1992). The latter observation stresses the importance of grazing management under conditions where the energy loss from exercise during grazing or obtaining water will become significant determinants of performance. Bell and Sangster (2023) noted the extreme conditions of the pastoral zone and especially the Northern Forest and the very poor reproductive performance there (McGowan *et al.* 2014). These factors do lead to low energy-use efficiency (Hunter 2010); however, the key metric that indicates the merit in the pastoral system is that there are very little, to zero, human available nutrients used in this production system to produce beef, unless finished in feedlots, as discussed below.

Sheep and cattle in the mixed farming zone

Most of the agricultural land with modified or improved pastures and crops is part of the mixed farming zone. Most farms retain a mix of crops and livestock because together they are far more efficient in the production of food than is either separately. Crops can benefit the production of meat and wool without compromising the yield of crops for food production. For example, there is a rapidly increasing trend to graze crops in the vegetative stage (Radcliffe *et al.* 2012). Such crops have a high metabolisable energy (>12 MJ ME/kg DM) and protein content (>20% DM) suitable for pregnant or rapidly growing ruminants (Masters and Thompson 2016) and allow establishment of pastures through deferred grazing (Thomas *et al.* 2015). Provided grazing ceases before stem elongation, the yield of harvested grain is usually maintained (Harrison *et al.* 2011). Grazing young crops without loss in grain yield facilitates animal production, with no trade off in the production of food from plants. At the other end of the crop-growth cycle, a single hectare of post-harvest wheat residue provides sufficient metabolisable energy to support one dry sheep equivalent for 50–100 days (Thomas *et al.* 2021*b*). If retained, this stubble may decrease subsequent crop yield (Kirkegaard 1995); conversely, loss of stubble through burning and conventional tillage may increase susceptibility to erosion and soil carbon depletion (Chan *et al.* 2003; Chan and Heenan 2005). The implications of grazing are less clear, with some evidence from overseas that the mixing of stubble residue in soil caused by livestock trampling compensates for the loss of stubble from consumption, with a consequent increase the soil organic carbon (Stavi *et al*. 2016). Soil compaction due to grazing stubble was once considered a risk to crop production. This risk is no longer supported by the literature (Bell *et al*. 2011*b*). Grazing therefore offers another opportunity to convert a crop waste product into food or fibre, with 3–6.5 million ha of crop residue grazed annually (D. T. Thomas, pers. comm.). Finally, livestock offer opportunities to turn failed crops into food (Bell *et al*. 2009). When the cost of harvesting crops that have been constrained by low rainfall, poor soils or other external factors exceeds the financial return, grazing provides a means of turning a financial loss into an animal product.

Crops do not just provide an option for increasing livestock production, they can also benefit from the interaction, meaning more efficient production of plant-based food. Traditionally, legume pastures have been used in rotation with crops, providing grazing while simultaneously fixing nitrogen, improving soil structure and contributing to the management of weeds, pests and disease (Bell *et al*. 2019). Other cropping options such as canola have joined the rotations, facilitated by the availability of cheap nitrogen fertilisers; pastures have been displaced and degraded (Howieson *et al*. 2000). With increasing fertiliser prices, expansion of acid soils and widespread herbicide resistance, there has been a refocus on breeding new pasture options for livestock and crop benefits (HC Norman and DG Masters, Livestock preference and feeding value as key determinants for forage improvement – why not ask the consumer? *Animal Production Science*, under review).

Beef feedlot and dairy cattle

More than 3.5 million head of cattle were turned off from Australian feedlots in 2022 (Atkinson 2022), representing a 100% increase in numbers over 20 years (Spragg 2018). Many of the 400 feedlots are sited close to the grain-producing regions of Australia, because costs of transport greatly increase the costs of feed and reduce the cost efficiency for those further away from grain-growing regions. Feedlot systems rely on a markedly different efficiency of conversion of feed intake to beef from cattle fed on either northern or southern pastures to be cost-effective. Typically, finishing diets for feedlot cattle contain 80–85% of concentrates, with processed grains, protein meals, molasses, minerals and feed additives and by-products being combined in mixer-wagons with 10–20% of forages, including cereal crop and maize silages, hays and straws, the latter being by-products of grain production. Spragg (2018) reviewed grain use in Australia for the 2017/2018 and 2018/2019 financial years, with wheat and barley being the predominant products (88% of all grain produced). Overall, grain fed to animals was about 30% of national production, with dairy and beef feedlots (48%) and chicken meat and eggs (31%) accounting for nearly 80% of feed grain usage. While it has been argued that feedlot systems are inefficient because the grain use would be better fed to humans, a large proportion of the grain used in feedlots, and indeed animal nutrition in Australia, is at the lower end of quality standards with respect to suitablility for human consumption and often just classified as feed grain, based on cultivar (e.g. sorghum, non-malting barley) and physical characteristics such as rain-damage and suboptimal specifications (Anonymous 2009, 2020, Black *et al*. 2023). More importantly, there is evidence of an NPC >1 (1.96), even when cattle are finished within a feedlot and fed a cereal-based ration with a significant amount of human-edible protein (Thomas *et al*. 2021*a*). The production system, combining grazing and feedlot, results in a net increase in human-edible protein. Further, beef and dairy cattle are fed by-products of ethanol production, human food production and cotton production. These products include dried distillers' grains, wheat by-products from flour manufacture, including wheat mill run and middlings, canola meal, sunflower meal, and whole cottonseed. Alternate uses for many of these products are limited and the use of these in cattle production lowers the costs of production for ethanol, flour, bread, processed wheat products, cooking oils and cotton.

Cattle for the local market are often fed for approximately 70 days in the feedlot, those for export and premium local markets 100–120 days and those for speciality long-fed markets, particularly Wagyu cattle, 200–230 days or more. In terms of GHG, many feedlot cattle are fed ionophores that reduce methane production (Ranga Niroshan Appuhamy *et al*. 2013), and the shorter time to slaughter than for growing cattle on pasture has a marked reduction in methane per kilogram of beef (methane intensity). The use of feedlots to finish cattle from the northern pastoral system represents a profound increase in GHG efficiency over traditional finishing at a much older age.

There are 1.4 million dairy cows in Australia and a similar number of young cattle, heifers and calves in the national dairy herd (Australian Bureau of Agricultural and Resource Economics and Sciences 2022*b*). Milk production per cow has increased from 2848 to 6170 L per annum over the 40 years to 2020. This change has significant effects on GHG emissions intensity as the proportion of methane ascribed to maintenance is reduced. Over this time, the industry has changed from being seasonal and pasture-based (Lean 1987) to less seasonal and with greater reliance on a wide range of fodder crops, feed supplements and concentrate inputs (Rugoho *et al*. 2017). Victorian farms evaluated for the Dairy Farm Monitor fed 61% of the metabolisable energy consumed as homegrown forages (Anonymous 2021). The forages used are almost exclusively improved and ryegrass species dominant, especially in southern Australia. Legume forages, predominantly clovers and also lucerne, are used. Other grasses include fescues, paspalum, kikuyu and there is increased use of maize silage. Herbs including chicory and plantain are used in mixed swards. Dairy cattle make great use of the by-products noted previously, but also brewers' grains, vegetable and fruit waste, confectionary, bread and biscuit waste. Spragg (2018) estimated the use of feed grain as 2.63 million tonnes for dairy in Australia. Beef is produced from dairy cattle with a high level of efficiency due to the reduced contribution to maintenance ascribable to the dual purpose of the cattle. Specifically, a beef female is not required to produce the calf. Increased use of sexed semen will allow increased production of beef semen on dairy cattle to produce crossbred cattle; however, Holstein steers are extensively used for beef production in the USA and Australian studies have confirmed that their eating quality matches that of beef breeds (Polkinghorne *et al.* 2023*a*).

In Australia, there is little human-edible food used to produce beef and milk. Many of the essential nutrients provided in beef and milk have zero human-edible food inclusion and this is the case for grass-finished beef. Using worst-case scenarios, that is assuming all grain fed was edible by humans, Lean and Moate (2021) found that 0–28% of lifetime nutrient intakes of energy, protein and essential fatty acids were derived from human-edible sources. As shown in previous examples, feeding these small amounts of human-edible foods to animals may leverage a net increase in human-edible protein (Thomas *et al.* 2021*a*). Cattle provide an efficient and productive means of turning human-inedible grain and food and ethanol by-products into high-quality foods, thereby reducing the costs of food overall and oxidation and gas generation from these wastes.

Pigs and poultry

The pig and poultry industries have grown exponentially over the past 60 years as local demand for meat (chicken and pork) and eggs has increased, but are small compared with their global counterparts. Each industry in Australia is dominated by a few large companies and the number of farms in each industry has decreased significantly over time. The large companies have adopted a vertically integrated structure and this has facilitated intensification and allowed rapid adoption of new technology. Each industry has sought the best technology from around the world and invested heavily in research and this has resulted in the acquisition of superior genetics, improved nutrition, better disease control, more effective management practices, and improved animal welfare. Together, these have resulted in significant gains in animal performance and feed conversion, boosting overall industry efficiency and productivity.

Australian breeding sow numbers are approximately 265 000, producing 5.2 million pigs annually. Most pigs are sold at bacon weight (100 kg), with a dressed carcass weight of 77 kg, resulting in 420 000 tonnes of pig meat produced annually (Dalgleish and Whitelaw 2021). The major pig production areas are in south-eastern Queensland, southern New South Wales (NSW), northern and western Victoria, south-eastern South Australia, and south-western Western Australia. Farrow to finish is the conventional structure of Australian pig farms and in this system, the farm breeds, farrows, weans and grows out pigs for sale. Production in Australia is largely confined to intensive indoor housing systems, with only 10% of commercial breeding as free range. The Australian production system is focused on the fresh pork market as this product has little competition from the import market of processed meat where 160 000 million tonnes is imported annually, or about 30% of total pig meat use in Australia (Spragg 2018). Currently, 42 000 tonnes are exported from Australia annually (Spragg 2018).

With approximately 600 million broilers producing ~1.2 million tonnes of chicken meat annually, Australia has mirrored the increased global demand for chicken meat (RMCG and BDO EconSearch 2020). Major centres of chicken meat production have developed near major capital cities on the eastern seaboard. Approximately 800 growers produce about 80% of Australia's meat chickens under contract to the major integrated or processing companies. Contract growers own the farm and provide the management, shedding, equipment, labour, bedding and other inputs to rear chickens from day-old to processing. The processing company provides (and owns) the chickens and provides feed, medication, and technical advice. Australian chicken meat is sold wholly into the domestic market, with some 70% being sold as fresh chicken (RMCG and BDO EconSearch 2020). Supermarkets represent the largest distribution channel, selling 40% of the fresh chicken meat. A very small volume of chicken meat is exported (4%). Chicken meat cannot be imported into Australia, to keep the industry free of major avian diseases. The excellent disease status of Australian poultry is maintained by strict biosecurity measures that exclude importation of poultry meat. This also has the effect of eliminating competition from chicken meat imports.

Australia's annual egg production is currently 6.6 billion eggs, with a flock size of approximately 21.2 million laying hens (AEL 2022). The industry is dominated by large-scale producers, who sell directly to large retail sellers. As with the chicken meat industry, commercial egg farms are situated close to the major cities, but, in recent years, the industry has re-established near major regional centres. Most of the flocks are found in NSW, followed by Queensland then Victoria, with eggs being produced by birds housed in cages (31.1%), free-range (55.6%), barn (11.3%) or speciality production (2.0%) (AEL 2022). About 85% of eggs are sold into the domestic market, with export being limited by production and transport costs (AEL 2022).

Profitability of the non-ruminant industries is driven by feed efficiency, the cost of feed, genetic improvement, animal/bird health status, and, for the pig industry, competition from imported pig meat. Feed-related expenses comprise 60–70% of total production costs, thus minimisation of feed costs is very important. This is in part achieved by least-cost feed formulation, which allows incorporation into diets of ingredients such as millrun, a co-product of flour milling, oil seed meals that are the residues of vegetable oil manufacture, and feed grade grains or grains that do not meet the criteria for human food manufacturing. For example, in 2021, some 45% of the NSW wheat harvest was downgraded to feed-wheat due to preharvest germination and fungal deterioration (Black *et al.* 2023). Where grains suitable for human consumption are used, they usually facilitate the conversion of a range of non-human edible by-products and food waste into human-edible protein. In the pig industry, for example, the NPC for an intensive Australian pork supply chain has recently been reported as 3.26, indicating the production of 3.26 times more human-edible protein than is consumed (van Barneveld *et al.* 2023). The authors are unaware of similar studies for the chicken meat and egg supply chains. Both the pig and poultry industries have become increasingly successful at using co-product meals by incorporating speciality feed additives into diets to improve digestibility with feed enzymes and dietary amino acid balance with supplementary amino acids (Ravindran 2013; Kebreab *et al.* 2016). These feed additives not only improve feed utilisation but substantially reduce emissions (Kebreab *et al.* 2016). Moreover, it is often asserted that land used for producing animal feed, especially for cereal grains, could be used to produce human food, such a transition may not be feasible as humans usually require different crops or cultivars that have different agronomic features and require different environmental conditions (Owens and Hansen 2011).

The other major strategy to offset feed costs is to increase production efficiency. For example, the laying rate of hens has increased from about 161 to 320 eggs per year from 1973 to 2016. Number of piglets weaned per litter and number of litters per sow per year have gradually increased, with sows currently producing 23.6 pigs/year (Dalgleish and Whitelaw 2021). The pig industry is less resilient to increases in feed costs than are the chicken meat and egg industries, due competition from imported pig meat. Chicken meat obviously has a significant cost advantage to other meats as the price of chicken has remained relatively constant for many years, reflecting efficiency of feed conversion which has improved from 2.5 in 1975 to 1.6 in 2020 (ACMF 2022). In achieving improvements in productivity the pig, chicken and egg industries do not use hormones or antibiotics as growth promoters.

Livestock and a sustainable environment

All of Australia's animal industries have strategies to reduce their environmental footprint and research priorities that include climate change and efficient use of resources. Across the red meat industries, Meat and Livestock Australia have asserted that these industries will be carbon neutral by 2030 (Meat & Livestock Australia 2021), with independent research suggesting that Australian sheep production for meat was climate neutral as of 2020 (Ridoutt 2021).

Cattle in the pastoral zone

In the extensive pastoral regions, careful management of stocking rates to prevent overgrazing can contribute to the maintenance of biodiversity. There is the opportunity for increased soil carbon sequestration through increased growth of pastures, woody shrubs, weeds and trees, emphasising that the animal and, indeed, all the agricultural industries need to adopt net-emissions metrics (Mayberry *et al.* 2018). Lam *et al.* (2013) found that conversion of cropland to grazing increased soil carbon more than did conservation tillage, crop residue retention or nitrogenous fertiliser application over 31–40 years. There is also the opportunity to reduce carbon loss through reduced burning of grasslands and increased carbon sequestration in soil using dung beetles (Mayberry *et al.* 2018). Altering land use management to increase reforestation, reduce savanna burning practices, reduced deforestation, and, to a lesser extent, increase woody biomass growth were considered likely to have the most substantial effects in mitigating the effects of beef cattle production on GHG emissions in Australia (Mayberry *et al.* 2018). It also appears likely that such strategies would further enhance the benefits of beef production in maintaining biodiverse habitats. Such management options are consistent with the conclusions of others (Masters *et al.* 2010; Thompson *et al.* 2023) that well managed animal systems can convert large quantities of non-edible biomass to high-quality foods, while providing diversity and respecting ecological principles that offer ecosystem services.

Sheep and cattle in the mixed farming zone

The introduction of annual crops and pastures into a landscape previously dominated by perennial plants has led to a level of degradation and dysfunction. Most notable is the prevalence of acid soils, the spread of secondary salinity and erosion of unprotected soils following plant senescence. While overgrazing and annual pastures have contributed to these problems, a well managed livestock component to a mixed farm offers opportunities to address the problems. Salinity results from elevated water tables related to a lack of growing plants for much of the year. There are options to use salt-tolerant perennial plants in saline areas or other perennials in non-saline areas to manage the water table (Masters *et al.* 2006). Both these options can be used for livestock, but there are not yet any viable perennial crops available for this purpose. The introduction of a mosaic landscape suitable for crops and plants offers a landscape with a function more closely resembling the natural state.

Given that sustainability also includes economic viability to the farm or enterprise, there has been a move towards higher cropping intensity in the mixed farming zone, with some evidence of increased profitability (Kingwell *et al.* 2020); however, there is also recent economic analysis, based on whole-farm profit of mixed enterprises, indicating that the optimal cropping proportion of the farm is between 40% and 60% (Young *et al.* 2020), with livestock occupying a significant proportion of the land. Together with the higher whole-farm profitability described by Young *et al.* (2020), there is strong evidence that a mixture of cropping and livestock reduces the risk of income variability. From a study of six sites within the mixed farming zones across four states, Bell *et al.* (2021) concluded that the risk-efficient frontier included a mix of crops and livestock at most sites. Significantly, this study assessed the risks when the crop and livestock enterprises were run independently and did not take into account the production synergies (Bell *et al.* 2021).

Dairy cattle

The carbon footprint of dairy largely reflects enteric methane production from cattle (70%), by nitrogen use for crop and pasture growth (3.5%), methane from manure (13%) and generation of nitrous oxide from urine (12%; Eckard and Clark 2020). The dairy industry, nationally and internationally, has considerable initiatives towards reducing its environmental footprint (Food and Agriculture Organization of the United Nations and Global Dairy Platform Inc 2019). However, the drive towards increased production efficiency through increased production by increased concentrate use, use of ionophores, fats and oils is the major factor reducing the intensity of GHG production (Eckard and Clark 2020; Lean and Moate 2021). There has been a significant focus on reducing ruminal methane production through use of ionophores, fats and oils, red seaweed, 3-nitrooxypropanol, tannins, essential oils and other interventions (Lean and Moate 2021). The final efficacy and practical choice of products to reduce ruminal methanogenesis as it interacts with production system and diet quality is still under intensive research (Davison *et al.* 2020). Significant reductions in the GHG footprint are also offered through improved reproductive efficiency, production of beef from dairy cows, increased longevity and nitrogen inhibitors that reduce volatilisation of urinary urea. Initiatives in California have provided evidence that large extensive dairies can become carbon neutral through a combination of co-generation and solar capture (Liu *et al.* 2021). Application of these techniques should, in combination with increased production efficiency, a focus on animal longevity and further adoption of rumen modification, result in carbon neutrality for many Australian dairies.

Pigs and poultry

The chicken meat, egg, and pig industries have a focus on reducing their environmental footprint in areas such as water management, waste minimisation, re-use and recycling, and reduction of greenhouse-gas output. Larger piggeries use methane gas to generate power for their facilities and sell surplus to the local power grid. It has been shown that the pig (Wiedemann *et al.* 2016, 2018) and chicken meat (Wiedemann *et al.* 2017; Copley and Wiedemann 2023) and egg (Copley *et al.* 2023) industries have had success in reducing their footprints. The largest impact that these industries have on the environment is growing the crops that are used for animal feed. Australia produces about 31.2 million tonnes of grain (wheat, sorghum, barley, oats, maize, lupins, and field peas, excluding canola and cottonseed), of which some 37% is used for domestic purposes (feed grain, flour grain, malting grain and retained seed; Spragg 2018). Of the 13.5 million tonnes of feed grain used by the animal industries, meat chickens (24.1%), laying hens (7.4%), and pigs (12.1%) consume some 5.9 million tonnes (Spragg 2018). The non-ruminant industries have reduced their reliance on imported soybean meal by increasing the concentrations of co-products and other protein meals, especially canola, in diets. There is growing interest in the use of human food wastes (Torok *et al.* 2022) and insect protein meals (de Souza-Vilela *et al.* 2019; DiGiacomo *et al.* 2019) as quantities become commercially available. This reduced reliance on traditional feedstuffs will reduce the environmental footprint of feed. Nevertheless, poultry production was shown to have the least environmental impact of all animal-sourced food, largely due to the efficiency of broiler chickens in converting feed into meat, which reduces the amount of feed and therefore the resources of land and water, required to produce each kilogram of meat (Copley and Wiedemann 2023).

Water use

The impact of animal production on freshwater resources is an additional challenge for the sustainability of the animal industries. It is particularly important in Australia, the world's driest continent. Globally, water is scarce and water-use assessment methods have been developed to measure water use by different commodities, communities and countries (Chapagain and Tickner 2012; Boulay *et al.* 2021). Calculating the water footprint is complex and varies with region, production system, and the type of water used (e.g. blue, green, grey or virtual; see Box 2). Estimates of the water footprint for animal production includes the water consumed by the animal, water used to grow crops for feed, and water required for meat (product) processing. The major component of water use for animal sourced foods is for crop production, especially irrigation (Ibidhi and Ben Salem 2020). In Australia, where most animal feed, both grains and forages, is produced by dry-land farming, water use is minimal compared with production systems in Europe and the USA, where there is much greater reliance on irrigation. Water-use comparisons of the same commodity produced in different production systems can be made only when there is complete transparency of the values used and their derivation. Recently, there has been a conscious effort internationally to build a consensus on water-use methodology for livestock production systems (Boulay *et al.* 2021).

Some systems of accounting for water use include rainfall and the rainfall used to produce crops such as grain. Depending on the method used to calculate water use to produce 1 kg beef, estimates range from 3 to 540 L of water by using the life-cycle approach to 10 000–200 000 L of water by using a water-footprint approach (which includes rainfall; Doreau *et al.* 2012). Moreover, when a detailed assessment was conducted over six different beef growing regions of

NSW, very different water footprints were obtained by Ridoutt *et al.* (2012), demonstrating the importance of local geography and confirming earlier Australian results (Peters *et al.* 2010). A similar result was also obtained when beef cattle production was compared among different regions of South Africa (Harding *et al.* 2017). It has also been established that as animal productivity and management improve, water-use efficiency of cattle increases (Klopatek and Oltjen 2022). Chicken meat requires the lowest amount water per kilogram produced, reflecting the efficiency of broilers turning feed into meat (Copley and Wiedemann 2023). Regardless, water use is always higher in the production of animal products than of crop products when expressed per kilogram of product. Nevertheless, when examining water data, beware of generalisations when comparing countries and products, which can be demonstrably misleading.

Across large areas of inland Australia, water is supplied to livestock by artesian bores. There has been considerable waste of water from these free-flowing bores, but recent capping of many of these bores has significantly reduced water losses (Wiedemann *et al.* 2015). Importantly, the extensive livestock systems in Australia generate products by using rainfall on land that is not suitable for other purposes (Doreau *et al.* 2012); hence, this valuable water resource is captured and not lost. Should this livestock system be penalised for using rainfall in this instance? Water is a precious resource and the interaction between livestock and water needs should be considered for each production system.

Importance of livestock and meat to Australian society

Livestock make a significant contribution to the Australian economy, employment and farming-system sustainability. The red meat and livestock turnover in 2020–2021 totalled A$67.7 billion (Meat & Livestock Australia 2022). The value of meat exported fluctuates, but is ~A$20–25 billion/year. Meat and livestock (including cattle, sheep, wool, milk, poultry, pigs and other livestock products) represent more than 42% of the value of Australian agricultural production and are the most dominant and growing components of the agricultural economy. Crops account for approximately 34% of the value of agricultural production, indicating that a narrative of diminished importance of livestock production to Australia is misleading. The value for meat and livestock has increased by almost 40% in the past 20 years. The growth in livestock prices reflects, in part, increased demand for protein in developing countries (Australian Bureau of Agricultural and Resource Economics and Sciences 2022*a*).

The red meat and livestock sector directly employed 191 700 people in 2020–2021, with another 230 000 being indirectly employed by industries servicing the sector (Meat & Livestock Australia 2022). Without livestock, many of the towns and communities, particularly those away from the coast, would cease to be viable; hence, the productive use of forest and rangelands is important to the economy and distribution of population within rural areas. The dairy and non-ruminant meat and egg sectors contribute significantly to the Australian economy, employment and many rural communities, especially on the southern half of the eastern seaboard. The pig industry contributes 36 000 jobs (APL 2020) compared with 4000, 58 000, and 46 000 for the egg (AEL 2022), chicken meat (ACMF 2022), and dairy (Dairy Australia 2022) industries respectively. In the same order, the industries contributed A$5.3, A$0.93, A$7.9 and A$4.7 billion to the Australian economy annually. The dairy industry also exports some 35% of production mainly as value-added products worth about A$3.3 billion (Dairy Australia 2022). All of the dollar figures cited for the different animal industries are farm-gate figures that do not capture the full economic impact. It has been estimated that every dollar of value added in processing of animal-sourced food products supports about A$3.0 of value-added elsewhere in the economy (Deloitte and Access Economics 2021).

Animal welfare

Australian animal industries have a social and ethical obligation to deliver demonstrable animal welfare improvements as has been clearly demonstrated (Hemsworth 2018; Salvin *et al.* 2020; Rivero and Lee 2022; Verdon 2022; Masters *et al.* 2023). Animal welfare is a key priority for government, industry and research (Barnett and Hemsworth 2009; Hemsworth *et al.* 2015; Colditz and Hine 2016; Kahn *et al.* 2017; Tilbrook and Ralph 2017; Colditz 2022). The industries endorse and abide by the relevant Australian Codes of Practice for the Welfare of Animals, and relevant State animal welfare legislation that cover production, transport and slaughter. Nevertheless, Australian producers in all animal industries are under a degree of pressure from animal welfare lobby groups and the public (Bray *et al.* 2017; Coleman 2018).

Australia is a dry and hot continent and alleviation of heat stress is a welfare issue, as is the long-distance transport of livestock. Mitigating the risk of heat stress in a feedlot is a welfare priority (Johnson 2018). By 2014, community pressure on the feedlot industry and production benefits led to ~80% of feedlots providing shade (Gaughan and Sullivan 2014). In the pig and poultry industries, community pressure associated with confinement of animals has been intense and this has resulted in significant changes. A decade ago only 10% of table eggs were produced free-range, with the remainder being produced by hens housed in cages. Half the table eggs produced in Australia now come from free-range production systems. Although this gives the impression of improved bird welfare, there are concerns regarding choke following pasture consumption and increased exposure to parasites (Bryden *et al.* 2021; Campbell *et al.* 2021). It should be remembered that broilers or meat chickens are predominantly housed in large barns and have never been grown in cages. Moreover, some 70% of broilers are farmed under an RSPCA-approved system, including 20% as free-range. The pig industry discontinued the use of dry sow stalls in 2017 and moved to group housing for pregnant sows. The pig industry would like to move away from farrowing crates that prevent piglets being crushed by the sow, but despite ongoing research, no satisfactory alternative has been identified that accounts for the conflicting needs of the sow and her litter (Barnett *et al.* 2001; Johnson and Marchant-Forde 2009).

There is a general acceptance that improving welfare also improves animal productivity through improved health and reduced medication and mortality (Dawkins 2017), improving the public image of the industries. Moreover, the cost of not maintaining a social licence to operate could be substantial, as it has been estimated that during the period 2015–2030, the potential accumulated loss could amount to A$3.9 billion for the Australian red meat industries (Fernandes *et al.* 2021). Good stockmanship is a cost-effective way of improving productivity and product quality (Barnett and Hemsworth 2009; Hemsworth 2018). It is an ongoing imperative that all livestock industry personnel are appropriately trained in animal husbandry and stockmanship to ensure animal welfare (Grandin 2018).

The path ahead

It is clear that the societal role of meat is being challenged with ideological and simplified logic, without substantiation from robust data-driven science. The Dublin Declaration is a first step to assemble an evidence-based narrative to underpin the essential role of meat in diet and health, a sustainable environment and society, economics and culture. Meat production, especially from ruminants, is a critical part of Australian agriculture, allowing both food production from non-arable lands plus making huge contributions to the circular economy of all agricultural pursuits. Accordingly, the Dublin Declaration is highly relevant to Australia.

Science alone is not perfect and can have suboptimal outcomes when undertaken within a siloed structure, especially when the biology and issues underpinning the augments are complex. In addition, effective communication is an essential ingredient when presenting the evidence and also for projecting the meat industry as a dynamic supply chain to attract young scientists into these career paths. A report by Polkinghorne *et al.* (2022) summarised an extensive global survey of meat scientists and industry practitioners and concluded that these broader concerns were deemed of at least equal importance to the traditional core disciplines of meat science and livestock biology.

Given the importance of meat in society, there is a need to urgently examine the best way forward for underpinning scientific funding, industry translation and collaboration in the area. Polkinghorne *et al.* (2023*b*) argued that in many countries, resources and staff associated with meat production have declined to critically low levels, threatening both fundamental research and industry support. In Australia, we are increasingly left with pockets of strength in some universities as State and Federal government funded institutions with expertise in meat are in decline. Scientists within the University system are also faced with challenges associated with reduced funding in the face of pressure to train more students, increased administrative load and a lack of base capital to maintain facilities to world standards. Clearly, the way forward is for even more emphasis to support strong multidisciplinary collaboration that will need significant and sustained Industry participation and support.

More recent examples in Australia of interdisciplinary research to tackle industry priorities are the Beef, Sheep, Pork and Poultry Cooperative Research Centres, which have delivered immense benefits to the beef, sheep, pork and poultry sectors of Australia (Keniry 2011; Griffith and Burrow 2015; Rowe *et al.* 2021). Substantial financial benefits have been quantified in the areas of animal management and welfare, genetic improvement, disease control and meat quality and yield. Importantly, the Cooperative Research Centres also come with a substantive education program, particularly in delivering industry-aligned postgraduate students that have been retained in the sector (Thompson and Rowe 2019). Another example is the Advanced Livestock Measurement technologies project for developing objective measurement of carcase meat yield and eating quality across the beef, lamb and pork industries (Gardner *et al.* 2021). There have also been efforts to upgrade the wastes of the red meat industry to valuable co-products funded by the Federal government (Ramirez *et al.* 2021). The benefits have been underpinned by the longevity of the programs (5–15 years), powerful heads of agreement that simplify sharing of intellectual property across institutions and finally embed intense engagement between industry and researchers. These programs have now finished and there is an urgent need for new and even bolder initiatives.

New developments need to bolster existing strengths in meat science and, importantly, expand collaboration to embrace the key themes of the Dublin Declaration. Thus, expertise in meat science, human nutrition, animal production, health and welfare, life-cycle environmental assessment, economics, communication and undergraduate/postgraduate education all need to be blended together in conjunction with industry (Mayberry *et al.* 2021). There is also the responsibility for scientists who are connected to the societal role of meat to connect outside their core disciplines. One example is the Nutrition Society of Australia, which brings together the disciplines of human and animal nutrition in yearly scientific meetings; unfortunately, the participation by animal science specialists has been dramatically declining in recent years. The final piece of the jig saw is to include mechanisms that strongly encourage international collaboration, which traditionally has been problematic in agriculture outside of programs that support developing countries. Thus, other countries outside one's own are typically seen as competitors rather than collaborators. The International Meat Research 3G Foundation, a not-for-profit international eating-quality research platform linked to the United Nations Economic Commission, is an example of a mechanism to underpin more collaboration across participating countries (Polkinghorne *et al*. 2023*b*). Clearly, the challenges underpinning the Dublin Declaration require urgent global collaboration and solutions.

Finally, there is an ongoing need to challenge false or inadequately substantiated information and to correctly contextualise the societal role of meat, so that the gains to different societies can be realised. There is a need to educate society through rational debate.

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Data availability. Data sharing is not applicable as no new data were generated or analysed during this study.

Conflicts of interest. All authors have an active research record in the livestock and/or the meat sectors. WLB and DGM have editorial roles with *Animal Production Science*. They were both blinded from the peer review process for this paper. The authors have no further conflicts of interest to declare.

Declaration of funding. All authors have undertaken research funded by national research bodies that relate to livestock. No specific funding was obtained to write this article or for MJM, DWP and ILJ to attend the Dublin Declaration meeting.

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