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The broad-based eco-economic impact of beef and dairy production: A global review

H.H. Meissner,[1] J. N. Blignaut,[2, 3, 4#] H.J. Smith,[2] C.J.L. du Toit[5]
[1] Milk SA, PO Box 1961, Brooklyn Square, 0075, South Africa
[2] Asset Research, Pretoria, South Africa
[3] School of Public Leadership, Stellenbosch University, Stellenbosch, South Africa
[4] South African Environmental Observation Network (SAEON), Pretoria, South Africa
[5] Department of Animal Science, University of Pretoria, Pretoria, South Africa

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Abstract

Cattle have been the focus of an intense debate between those concerned about, among other things, the possible negative effects on global warming, land degradation, food competition, and human health and those who are positive toward the possible role of cattle in maintaining global socio-economic and environmental sustainability. This paper reviews the pros and cons in view of a projected increase in demand for animal-based foods and therefore in cattle numbers. Analyses of cattle numbers and foods from various literature sources suggest gross overestimation towards 2050. Although cattle are responsible for a major portion of methane emissions, the atmospheric accumulation of methane from cattle could possibly be overestimated due to methane's short atmospheric lifespan, recent calculations of enteric fermentation, and methane's warming potential, and the role of cattle in carbon sequestration and being a sink. Since carbon sequestration has more potential than emission reduction in limiting global warming, photosynthetic capacity should be maximised. It is concluded that whereas concerns about animal welfare, zoonosis, and antimicrobial resistance should be addressed, the call for a reduction in global cattle numbers because of the perceived negative effects mentioned above may be unwarranted. A reduction in cattle numbers could limit the advantage of livestock-related carbon sequestration and therefore largely defeat the objective of limiting global warming.

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#Corresponding author: James Blignaut; jnblignaut@gmail.com

Introduction

Currently there is an intense debate between those against the use and expansion of animal-based protein, and those not unduly concerned about the use of such to combat global hunger. Typical concerns against animal-based protein relate to rising greenhouse gas (GHG) emissions (Steinfeld *et al*., 2006), land and resource use (FAO, 2009; Bryan, 2011; Eshel *et al*., 2014; Yitbarek, 2019), land degradation (Dregne, 2002; Steinfeld *et al*., 2006; Nkonya *et al*., 2016), negative effects due to animal welfare (Johnsen, 2009; Smith *et al*., 2013), antimicrobial resistance (AMR) (Ritchie & Roser, 2017; WHO, 2017), zoonosis (UNEP & ILRI, 2020), and general environmental and human health concerns (Simões, *et al*., 2021; Chen *et al*., 2013; Abete *et al*., 2014; Bouvard *et al*., 2015). These concerns are raised at a time when it has been projected that food requirements will increase by 50–70% towards 2050 (Wmaran, 2012; Smith *et al*., 2013) and, from a livestock perspective, at least a doubling in demand for meat (FAO, 2009; Thornton, 2010) and even more for dairy (Yitbarek, 2019). These anticipated increases are due to the rise in the global population and the demand for animal-based protein increasing at the expense of staple foods as per capita income in transition and developing countries increase (FAO, 2009; Meissner *et al*., 2013a). The livestock sector is also well-positioned for this challenge since it occupies approximately 30% of the ice-free terrestrial surface of the earth and

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80% of marginal land (Thornton, 2010). In 2010, it contributed more than 40% of the global value of agricultural output (Scollan *et al*., 2010; Salmon *et al*., 2020), employed 1.3 billion people, and supported 600 million smallholder farmers in transition and developing countries (Lowder *et al*., 2021).

While most people recognise the importance of dealing with animal welfare, AMR, and zoonosis, many believe that the concerns raised above can be either offset or that the concerns are misplaced. These authors share the opinion that GHG emissions can be limited by production efficiency (Capper *et al*., 2009; Capper, 2021), dietary and supplementary means (Broucek, 2018; Eckard & Clark, 2018; Kinley *et al*., 2020), carbon sequestration (Franzluebbers, 2010; Poeplau *et al*., 2015; Conant *et al*., 2017), grazing management (Teague *et al*., 2011; Wang *et al*., 2015; Blignaut *et al*. 2022) improved genetics and other means. They also do not regard animal needs as being in direct competition with human foods (Ederer *et al*., 2022) as herbivore livestock primarily use materials which cannot be digested by man (Mottet *et al*., 2017) and often, to that effect, occupy spaces which cannot be cultivated (Jones & Thornton, 2009; Mottet *et al*., 2017). In addition, they regard animal-based foods as vital to human development because of nutrient density and high bioavailability (Neumann *et al*., 2002; Semba *et al*., 2016; Beal *et al*., 2017; Day *et al*., 2022) and do not subscribe to the notion that animal-based foods are a threat to human health (Soedamah-Muthu *et al*., 2011; Hjerpsted & Tholstrup, 2016; Zeraatkar *et al*., 2019a; Zheng *et al*., 2022).

Given the intense debate, and the importance thereof, concerning the matters highlighted above and others such as social, cultural, economic, and political impacts of livestock production, the question is whether an increased production for animal-based protein is attainable without negative consequences. In this paper, we focus on beef and dairy cattle, reviewing some of the most recent research on the contribution of cattle to the economy, social wellbeing, and food security as well as environmental concerns.

Abundance and distribution of cattle

Population statistics

Between 1800 and 2006, cattle (non-cattle bovines not included) constituted 32–37% of herbivore livestock species and increased in number from approximately 420 million to 1.4 billion (Robinson *et al*., 2014; Smith *et al*., 2016). On a biomass basis, cattle constitute roughly 70% of herbivore livestock species which include cattle, buffalo, sheep, and goats (calculated from Smith *et al*., 2016), illustrating the overwhelming influence which cattle can have on land use, natural resources, and the environment.

However, there is no consensus as to the global population of cattle (see Annexures 1 and 2). According to the FAO (Annexure 1), the global herd is increasing monotonously on a year-on-year basis. When considering individual country statistics and also consulting various sources, there are some marked discrepancies (Annexure 2), questioning the absolute numbers and the steadily increasing trend. These growth discrepancies are highlighted in Table 1. Not only does the growth rate vary much from year to year within a given country because of climatic extremes, disease, and demand but it also varies much among different countries. The countries listed in Table 1 are the ones with the largest herds. For example, the cattle population change in Brazil varies between -2.5% (2013) and +10% (2020). Russia saw an increase of 21.8% in 2013 and a decline in practically all the years thereafter. China's herd also fluctuated between growth rates of -12.1% and +19.8%. These large discrepancies in both the absolute size of the global herd, as well as the relative change between years and countries, are disconcerting given the importance of cattle in a global context and the weight placed on the FAO statistics to determine policies with a global reach and significant local impact.

Table 1 The year-on-year percentage change in cattle populations

Country	2012	2013	2014	2015	2016	2017	2018	2019	2020
Brazil	-0.3%	-2.5%	7.6%	2.8%	0.9%	1.4%	-0.9%	3.6%	10.0%
India	-0.9%	2.1%	-3.1%	-	-	-0.5%	0.0%	-	-
China	3.4%	5.6%	5.7%	-11.2%	-4.6%	0.5%	-12.1%	19.8%	4.6%
Russia	-2.1%	21.8%	-19.2%	-4.6%	0.5%	-0.5%	-1.6%	-1.1%	-0.6%
United States	-1.6%	2.8%	-3.6%	2.9%	1.0%	1.3%	0.6%	-0.3%	-0.3%
EU*	-	1.0%	1.9%	1.0%	0.0%	-2.3%	-1.5%	-0.8%	-0.9%
Ethiopia	-	-	-1.8%	-	-	2.4%	2.8%	-1.8%	-
Argentina	-1.4%	0.6%	-1.5%	2.7%	0.6%	1.3%	0.7%	0.0%	-1.3%
Pakistan	-	-	6.4%	-	-	3.7%	3.8%	-	-
Mexico	-	-	3.8%	-	-	-6.2%	9.4%	-	-
Australia	0.6%	-0.4%	3.2%	-6.2%	-8.8%	4.8%	-0.4%	-9.2%	-2.1%
Bangladesh	-	-	5.3%	-	-	0.4%	0.8%	-	-
Colombia	-	-7.9%	4.5%	-	-	-	-	-	-

Sources: see Annexure 2
EU* - EU excluding the UK

Country trends

Cattle numbers for countries with >20 million cattle are shown in Tables A1 and A2 (of Annexure 2) and the countries with the ten largest herds are shown in Figure 1. These ten herds comprise approximately 60% of the global cattle population. Brazil has the most cattle in the world and the number is increasing, largely driven by exports, with the total population recorded as 253 million in 2020 (World Data Atlas, 2020; Cattle Industry, 2021).

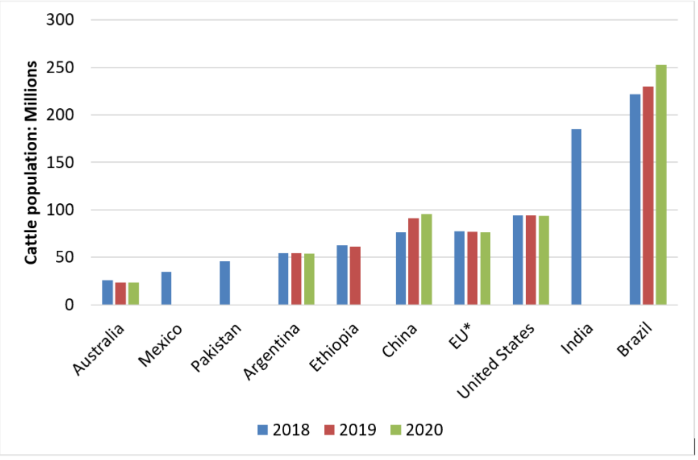

Figure 1 Countries with the ten largest herds in the world
Source: FAOSTAT (2021); *EU excluding the UK

When considering the trend since 2009 (as depicted in Tables A1 and A2), the herds in some countries increased (such as Brazil, China, Ethiopia, Pakistan, and Colombia), while herd sizes remained unchanged in India, the USA, EU, Argentina, Mexico, and Bangladesh, and it declined in Australia, Russia, and Sudan. There is no marked difference between developed and transition or developing countries as there is representation of the trends of increase, constant, and decrease in all of these nations. In earlier publications (Scollan *et al*., 2010; Meissner, 2012), there were indications that increases in production in developed countries resulted primarily through increased efficiency, whereas in developing countries, it resulted primarily through increasing numbers; the implication being that more pressure could be put on resources and degradation of land in developing countries (Weber and Horst, 2011; IUCN, 2017; ILRI *et al*., 2021). While this may be true for Ethiopia (Ethiopia NDC Report, 2021) and possibly a limited number of other developing countries, in general, the trends in Table 1 do not support the conclusions in these earlier publications. However, this does not negate the interpretation that efficiency of beef production has not made vast strides in particular countries. For example, in 2007, beef production systems in the USA (Capper, 2011a) required 69.9% of the animals, 81.4% of the feedstuffs, 87.9% of the water, and 69.0% of the land to produce 1 billion kg of beef compared to 1977; waste output was reduced to 81.9% manure, 82.3% CH_4, and 88.0% N_2O. Or in dairy, as another example, milk production in the USA increased by 24.9% between 2007 and 2017. This was achieved by 25.2% less cows, resulting in a reduction in methane emissions of 19.1% and 18.5% in nitrous oxide (Capper & Cady, 2020).

Socio-economy

Contribution to agro-economy

Livestock provide more than half of the value of agricultural output in developed countries through production and trade, but proportionally less in medium income and developing countries. As a group, the latter nevertheless amounts to approximately one third (Upton, 2004; Smith *et al*., 2013; Baltenweck *et al*., 2020); the world average being approximately 40% (Scollan *et al*., 2010; Salmon *et al*., 2020), with the world average having remained constant over time (Baltenweck *et al*., 2020). Specifically with respect to cattle, beef in developed countries accounted for 27% of total meat production in 2007 and 19% in developing countries (Meissner, 2012). Recently, beef production remained constant, for example, between 2016 and 2021 at <70 million metric tons (Statista, 2021b). The constant value again casts doubt on the consistent increase in cattle numbers as estimated by FAOSTAT (2021). Beef's share of total meat production has declined from 32% in 1990 to 21% in 2020. The bulk of production, and therefore consumption, now comes from pork and chicken (76%) (Blaustein-Rejto & Smith, 2021; Statista, 2021b).

Globally, livestock is a substantial asset of more than $1.8 trillion (Ederer *et al*., 2022). In transition and developing countries, the impact of livestock is staggering (Smith *et al*., 2013). Livestock production and marketing are essential to the livelihoods of more than 1 billion poor people in Africa and Asia, which is one seventh of the global population. Beef production and marketing in West Africa supports 70 million people; dairy supports 124 million people in South Asia, and 24 million in East Africa, whereas small ruminants support 81 million people in West Africa and 28 million in southern Africa. Estimations also show that more than 80% of poor people in Africa and up to 66% of poor people in India and Bangladesh keep livestock (FAO, 2009).

Contribution to social wellbeing

Livestock products in developed countries are sold in well-defined value chains with predicted and future markets and prices, whereas the value of livestock in poor and developing countries is much more than the market price of the product. This discrepancy also reflects the challenges that livestock-keepers face, such as constrained finances and access to information and services, as well as landlessness (Randolph *et al*., 2007). The following benefits to keeping livestock in developing countries can be listed:

(1) Livestock are used to accumulate wealth and in pastoral communities and are often the only major asset (De Haan *et al*., 1997; Randolph *et al*., 2007; Abay & Jensen, 2020). Small and large animals constitute a "savings account" (Baltenweck *et al*., 2020) used to purchase agricultural inputs; invest in other income-generating activities; or pay for expenses such as education, weddings, medical bills, and funeral costs.

(2) Livestock contribute to staple food production by providing manure, contribute to land preparation, and provide ready cash to buy planting materials or fertiliser or to hire labour for planting, weeding, or harvesting. The contribution of livestock can thus increase the area of land cultivated, the yields and productivity achieved, the feed produced from crop residues, and, through enhanced nutrient recycling, the sustainability of the farming systems (Randolph *et al*., 2007; Smith *et al*., 2013).

(3) Although the use of draft power is generally decreasing globally, in regions such as sub-Saharan Africa, it continues to contribute substantially to food production. Draft power enables more land to be cultivated, allows farmers (especially women) to escape the burden of manual tillage, and permits land to be cultivated before the rains have softened the soil, thereby increasing timeliness of farming operations (FAO, 2011a; Smith *et al*., 2013).

(4) Livestock can provide a buffer and additional income in times when harvests fail or other disasters strike.

(5) In many societies, small ruminants are often owned by women, who may also control any income obtained from their sale.

(6) Improving women's access to inputs and services has the potential to reduce the number of malnourished people in the world by 100–150 million (FAO, 2011b).

(7) Livestock are an important asset for investment and insurance for hundreds of millions of rural poor, in situations where banks are often too remote and the banking systems too unreliable for safeguarding any savings a smallholder might accumulate (De Haan *et al*., 1997).

The combined impacts of meeting nutritional needs, providing income, and reducing risks make livestock one of the most important components of global agriculture, but specifically for the poor.

Food security

World trade

The rapid growth in global demand for livestock products that has occurred over the last quarter of a century, has been characterised as "the Livestock Revolution" (Upton & Otte, 2004) and is expected to continue. It is largely driven by increases in per capita income, population growth, and urbanisation of developing countries. Demographic changes, urbanisation, and economic growth in the developing world, particularly in emerging (transition) countries such as Latin America and Asia, are rapidly changing food consumption patterns (Guyomard *et al*., 2013). Developed countries achieved the food transition process in a time period of more than a century. Emerging and other developing economies are now following a similar consumption pattern but at a considerably accelerated rate; according to Popkin (2006), the transition is reduced to 20 years in emerging countries and 40 years in other developing countries.

Table 2 shows export prospects of beef and dairy towards 2026 of major exporting countries, predicting a substantial growth in the market of 19.5% and 22.5%, respectively.

Table 2 Key countries exporting beef, veal, and dairy products and exporting prospects

	Exports 2016 (000 tonnes cwe)**	**Projected export growth 2016–2026 (000 tonnes cwe)****	**Exports 2016 (000 tonnes)#**	**Projected export growth 2016–2026 (000 tonnes)#**
	Beef and veal		Dairy products	
Argentina	230	463	424	17
Australia	1 913	300	195	108
Canada	619	100		
Brazil	1 893	633		
EU^	462	-138	1 946	715
India	1 655	275		
New Zealand	621	-91	2 418	548
USA	1 413	188	885	145
ROW*			1 955	224
Total	8 806	1 730	7 823	1 757

^EU including the UK; *ROW = Rest of the world; **CWE = Carcass weight equivalent; #Dairy products are whole and skimmed milk powder

Source: Calculated from Horizon – Market Intelligence (2017)

Argentina, Australia, and Brazil are expected to be the dominating countries in beef and veal with substantial exports also from the USA and India, whereas the influence of Europe and New Zealand will decline. Although much of the trade occurs within developed countries, a major portion goes to transition and developing countries. In concert with import and export, meat production in transition and developing countries will continue to be dominated by China and Brazil, the former benefitting from economies of scale as production moves towards increasingly commercial enterprises, and the latter from resource abundance and a devalued currency (Horizon – Market Intelligence, 2017).

In dairy, New Zealand and the EU dominate the market (Table 2). The EU is projected to show export growth in the four, main dairy export products, namely cheese, butter, skimmed milk, and whole milk powder (Horizon – Market Intelligence, 2017). Export expectations from other key exporting nations are more conservative. However, New Zealand is expecting to see whole milk powder exports rise by 22% between 2016 and 2026, thereby maintaining a 53% share of the overall global market. The major share will go to China and south-east Asia and the growth is expected to continue.

Demand for meat and milk

It has been projected that a doubling in meat production (FAO, 2009; Thornton, 2010; Yitbarek, 2019), even more in beef production, *per se* (Cooke *et al*., 2020), and a quadrupling in milk production between 2003 and 2050 (Bryan, 2011; Yitbarek, 2019) will be required to meet the increasing demands of the global population by 2050. The question arises if the demand can be met as it will require sharp increases in cattle numbers and productivity. The projection for global numbers is an increase from 1.5 billion in 2000 to 2.6 billion in 2050 (Rosegrant *et al*., 2009; Thornton, 2010), which would require an annual increase for developed countries of 0.6% between 2005 and 2030 and 0.2% between 2030 and 2050 and a corresponding increase in developing countries of 2.0% and 1.3%, respectively (Rosegrant *et al*., 2009; Yitbarek, 2019). This is unrealistic since (1) the global cattle population in 2000 was still <1.3 billion as implied above and shown in Figure A1(A), and (2) if the cattle population numbers of FAOSTAT (2021) as depicted in Figure A1(A) in Annexure 1 are accepted, extrapolation from the linear regression equation indicates a cattle population of only 1.76 billion in 2050, and from the polynomial regression equation, only 1.47 billion. Taking into consideration inaccuracies such as country numbers and environmental influences, it seems unlikely that cattle numbers will exceed approximately 1.6 billion by 2050.

In addition to the argument pertaining to the size of the global herd, beef production has largely stagnated at <70 million metric tonnes per annum between 2016 and 2021 (Statista, 2021b). It is accepted that productivity in terms of efficiency and carcass weight can increase. Carcass weight increased from 160 kg in 1961 to 215 kg in 2019 (FAOSTAT, 2021; 216 kg as calculated in Figure A1(B)) and it is projected to increase to 227 kg in 2050 (Nikos & Jelle, 2012: Yitbarek, 2019), which is unrealistic as most cattle in developing countries with the largest expected increase in cattle numbers, are not fattened, but slaughtered in a lean condition, even emaciated.

Similarly, the required milk production is unrealistic since current production levels per cow in developed countries are becoming difficult to exceed without major implications to animal health and welfare, and high investments in genetic improvement and feed stocks will be required in developing countries. Production levels in selected developing countries (Bangladesh, India, Jamaica, Peru, Senegal, Tanzania, and Thailand) vary between 250 and 3 000 kg/cow/year (Knips, 2005), and for the continents (Capper, 2011b), it ranges: sub-Saharan Africa (excluding South Africa) at 250, South Asia at 1 000, Near East and North Africa at 1 300, Central and South America at 1 700, South East and East Asia at 2 800, Russian Federation at 3 000, Eastern Europe at 3 900, Oceania at 4 400, western Europe at 6 100, EU27 at 7 300 (Eurostat, 2021b), and North America at 8 800 ℓ/cow/lactation.

The per capita demand must be considered in the context of the dichotomy of abundance in the developed world and low consumption in the developing/poor countries, although vast changes are expected with increasing affluence as poor countries rise during the transition phase (Delgado, 2003; FAO, 2009; Smith *et al*., 2013). For example, the per capita demand for meat in China increased dramatically from 3.6 kg in 1961 to 52.4 kg in 2002 (Scollan *et al*., 2010). In developed countries, the demand for meat and milk (including other dairy products) was predicted to increase from 78 kg and 202 kg per capita per annum from 2002 to 83 kg and 203 kg, respectively, per capita per annum in 2015. The corresponding figures for developing countries were 28 kg meat and 44 kg milk per capita per annum from 2002 to 32 kg meat and 55 kg milk per capita per annum in 2015. In general, the annual demand for meat is expected to increase by between 6 and 23 kg per person worldwide by 2050, and the absolute increase will be greatest in Latin America, the Caribbean, East and South Asia, and the Pacific, with demand doubling in sub-Saharan Africa. As argued above, these demands will have to be met primarily by pork and chicken, as beef (and also sheep and goat meat) production is unlikely to increase to the projected requirement. In fact, the demand for beef may already be declining in Europe: EU consumption of beef reached a high in 1985 at 25 kg per capita per year, but from then has steadily declined to 16 kg (carcass equivalent). This is low compared to other major beef consuming countries in the world (e.g., 35 kg in Australia, 37 kg in the USA, 41 kg in Brazil, and 59 kg in Argentina) (Hocquette *et al*., 2018).

The dichotomy of developed versus developing countries is best illustrated by the per capita demand for meat at the extremes of developed and developing countries, such as 125 kg meat in the US, 146 kg in Denmark (Scollan *et al*., 2010), 59–60 kg (beef alone) in Argentina (Arelovich *et al*., 2011; Hocquette *et al*., 2018), 13.3 kg/annum in sub-Saharan Africa (FAO, 2009), and 3.5 kg/annum in Ethiopia (Yitbarek, 2019). Excluding Ethiopia, these figures equate to per capita consumption of 165 g/day, 200 g/day, 80 g/day, and 20 g/day, respectively (Meissner *et al*., 2013a), reflecting a tenfold difference from highest to lowest. To put these numbers in perspective, recommendations for meat intake from an essential nutrient intake point of view range from 50–100 g per capita per day (McMichael & Ainslie, 2010) to 100–110 g per capita per day according to the World Cancer Research Forum (IMS, 2012), and 150 g per capita per day (Smith, 2012). Therefore, to meet the demand for animal protein and associated nutrients, production as far as possible (given the limitations in livestock production increases, and imports to developing/poor countries), should in fact be escalated and not reduced.

Contribution to human health

Diets of many people in poor and middle-income countries, and even those of some populations in rich countries, tend to be low in high-quality protein, iron, vitamin A, zinc, calcium, and other nutrients (Murphy & Allen, 2003; Semba *et al*., 2016; Beal *et al*., 2017). While there is considerable variation across different types of animal source foods (meat- or dairy- or egg-based), the majority are dense in energy, multiple and essential micro- and macronutrients, and amino acids (Neumann *et al*., 2002; Liday *et al*., 2022), some of which are rarely found in plant source foods (e.g., vegetables, grains, legumes, and nuts), such as vitamins B12 and D. Plant source foods do contain essential micronutrients, but for some, such as iron, the captured form makes it less readily absorbable by the human body (Murphy & Allen, 2003). For others, such as carotenoids (for production of vitamin A), large food quantities are needed to meet the requirement (Neumann *et al*., 2002; Murphy & Allen, 2003). Most animal source foods also contain high-quality proteins, comprising all essential amino acids (Neumann *et al*., 2002). Diets without animal source foods must typically include a wider variety of foods and in larger quantities to provide all required amino acids (Young & Pellett, 1994) and may require supplements for certain vitamins.

Infants, young children, adolescents, and pregnant and lactating women have higher nutrient requirements per kg bodyweight and are more vulnerable to nutrient deficiencies and associated negative health outcomes if they consume insufficient amounts of key micronutrients (Neumann *et al*., 2002; Murphy & Allen, 2003; Ferrara *et al*., 2017). As animal source foods tend to be dense in many nutrients, relatively small amounts can be eaten to meet multiple requirements, making these helpful additions to the diets of vulnerable people groups, particularly young children (from 6 months of age) (WHO, 2014). There is also some evidence of associations between animal source food consumption and reduced risks of stunting (Neumann *et al*., 2003; Neufeld *et al*., 2021) and improved micronutrient status, growth, and/or cognitive performance (Neumann *et al*., 2003; Iannotti *et al*., 2017). It should, however, be noted that it is difficult to make unequivocal conclusions in studies such as these as numerous other impacting factors cannot always be controlled. The same applies to an analysis of evidence on health implications of animal source foods discussed in the next paragraph. The most acceptable way is to rely on studies using collective investigations with a meta-analysis methodology, and reviews.

Considering that recent studies show an association between consumption of unprocessed red meat and processed meat and adverse health consequences, including increased risk for cancer (Bouvard *et al*., 2015), all-cause (Schwingshackl *et al*., 2017), cardiovascular mortality (Abete *et al*., 2014), and stroke (Chen *et al*., 2013), dietary guidelines have generally endorsed limiting meat intake (Health Canada, 2019; Public Health England, 2019; U.S. Department of Health and Human Services, 2019). There are many contradictory studies though, for example, Larsson & Orsini (2014), Zeraatkar *et al*. (2019b) and Iqbal *et al*. (2021), which did not find significant associations between unprocessed red meat and mortality or major cardiovascular disease (CVD). Iqbal *et al*. (2021) did, however, find that a higher intake of processed meat was associated with higher risk of mortality and major CVD. This is also supported by Larsson & Orsini (2014) and Wang *et al*. (2016). Regarding cancer, Han *et al*. (2019) and Zeraatkar *et al*. (2019b) reported that diets restricted in red meat have little or no effect on cancer mortality and incidence, and in an overall conclusion, Zeraatkar *et al*. (2019a) stated: “The magnitude of association between red and processed meat consumption and all-cause mortality and adverse cardiometabolic outcomes is very small, and the evidence is of low certainty”. This statement has recently been supported by Lescinsky *et al*. (2022) in a Burden of Proof study and by Zheng *et al*. (2022) in a biomarker-calibrated study.

A summary of association results between the intake of milk and dairy products and human health reveals the following: the assumption that saturated fat can lead to increased plasma cholesterol which is associated with risk of CVD (Pedersen *et al*., 2011), and since full-fat dairy products contain saturated fat, most dietary guidelines recommend the consumption of low-fat dairy products. However, the evidence for a link between dairy consumption (including full-fat products) and CVD shows neutral, or even a modest beneficial, effect (Astrup *et al*., 2010; Soedamah-Muthu *et al*., 2011). Kratz *et al*. (2013) concluded that the observational evidence does not support the hypothesis that dairy fat or high-fat dairy products contribute to obesity or cardiometabolic risk and suggests that high-fat dairy consumption within typical dietary patterns is inversely associated with risk of obesity. This is supported by Feeney *et al*. (2017), who showed that higher intake of dairy (milk and yogurt) was associated with a lower body mass index, %body fat, waist circumference, and waist-to-hip ratio, as well as lower systolic and diastolic blood pressure. Results furthermore suggest minimum or no risk for CVD and intake of cheese (Hjerpsted & Tholstrup, 2016) and even a non-linear relationship with maximum cheese intake at ~40 g/d for maximum protection (Chen *et al*., 2017). Thus, it can be concluded that even at relatively high intakes, there is little evidence that milk has any significant adverse effects on health and may even be protective against CVD, metabolic syndrome, and colorectal cancer. Whereas other dairy products certainly contribute to consumption of saturated fatty acids, evidence for either negative or positive effects on health are limited (Salter, 2013; Godos *et al*., 2020).

Deductions from the discussion on meat and dairy products *per se* are that their contribution to the risk of metabolic diseases is low, and over-consumption resulting in obesity should rather be the concern (Wilson *et al*., 2005; Popkin, 2006; Salter, 2013). Eating energy-dense diets, in particular rich in carbohydrates and sugar, and excess animal source foods, combined with sedentary lifestyles, has resulted in obesity mostly in developed countries, but also in developing countries due to energy–protein imbalances. A highly likely outcome over time is that a significant number of obese individuals will become insulin resistant and develop metabolic syndrome (Wilson *et al*., 2005; Salter, 2013), a cluster of risk factors that predispose the individual to both CVD and type 2 diabetes.

Environment

Greenhouse gas emissions

Methane emissions and the biogenic carbon cycle

All food production systems have an environmental impact. Livestock production has been singled out as a major cause of climate change (global warming) (Steinfeld *et al*., 2006; IPCC, 2007). The concern is primarily associated with ruminant livestock being a comparatively large source of methane (CH_4) emissions, which is perceived to have a much higher warming contribution (52%) than carbon dioxide (CO_2, 13%) and nitrous oxide (N_2O, 35%) (Van Hooijdonk & Hettinga, 2015). The main source of ruminant CH_4 is enteric fermentation. Enteric CH_4 contributes approximately 6% to global anthropogenic GHG emissions and 40% to all livestock emissions (Gerber *et al*., 2013). Methane is also an attractive amelioration target for short-term gains in global warming abatement, since it has a much shorter lifetime than CO_2 in the atmosphere of 8–12 years (Muller & Muller, 2017; Allen *et al*., 2018) and therefore all countries must target CH_4 reduction.

For mitigation purposes, it is more relevant to express GHG emissions (and CH_4) in relation to the amount of product produced, that is, to consider the contribution to food security at the same time. It also provides a measure of efficiency and partly reflects the amount of product produced in relation to the number of non-producing animals (Meissner *et al*., 2013b). For beef cattle, the proportion of non-producing animals (including cows and heifers) is high compared to dairy cattle, where the cow is also the producing animal. Greenhouse gas emissions in kg CO_2 equivalent (e)/kg product in life cycle assessments for developed countries at the farm gate (De Vries & De Boer, 2010) are: beef = 14–32 and milk = 0.84–1.4, and when grass burning, slaughtering, and processing in the case of beef are added, it is 25–35 kg CO_2 e/kg; for milk, the numbers increase to 1.3–1.5 kg CO_2 e/kg after processing. The number for sub-Sahara Africa is ~2.7 kg CO_2 e/kg milk, illustrating the effect of low and inefficient production systems (Capper, 2011b). Within the context of the anticipated increases in demand in the future, it is imperative that efficient systems should be followed with high levels of production and turnover, while not compromising the natural resources and the environment.

Factors which need to be considered when considering CH_4 emissions of cattle and which have mostly not been taken into account as yet, relate to the IPCC acceptance of the global warming potential (GWP) of CH_4, the generally accepted amount of CH_4 produced in enteric fermentation, and accounting in GHG emission calculations for the contribution of the animal itself as being a carbon sink and not merely a source of emissions. Being comparatively new in the literature, these require more detailed discussion.

In GWP, the conventional calculation (GWP100) accepts the GWP of CH_4 as being 28 to 34 times the warming potential of CO_2 (EPA, 2018). Recently, this has been contested (Muller & Muller, 2017; Allen *et al*., 2018; Lynch *et al*., 2020). Muller & Muller (2017) contested this on account of a much lighter molecular weight of CH_4 compared to CO_2, a half-life of CH_4 in the atmosphere of 8.6 years, and an exponential decaying rate, which together indicate that half of its effect is realised in the first 8.6 years and three quarters after approximately 17.2 years, whereafter it filters progressively towards infinity (Figure 2). This results because CH_4 is removed from the atmosphere by chemical reactions, primarily with the hydroxyl radical and by chemical reactivity with soil. Photosynthesis through the biogenic carbon pathway plays a significant role (Figure 3). In contrast, for CO_2, the primary mechanisms for removal from the atmosphere involve absorption into the oceans and biomass, which can last up to 1000 years. Because of the regular removal of CH_4, and if more CH_4 is not added to the atmosphere than that removed, the net result is a shifting warming effect, but on average at much lower levels than that which is acceptable in GWP100. The approach of Allen *et al*. (2018), Lynch *et al*. (2020), and Smith *et al*. (2021) is not dissimilar, emphasising the changing nature of the warming effect. These authors use a finite period of 20 years to capture the decaying nature of CH_4 and calculated, using the equation of Smith *et al*. (2021):

$$E^*t = 128 \times ECH_4(t) - 120 \times ECH_4(t-20), \qquad (2)$$

that if a cut-off point of 20 years is considered where ECH_4 is CH_4 emissions for time t and time t-20, then the warming potential can be as low as 128–120 = 8 times that of CO_2. This approach has become known as GWP* and has progressively been applied in life cycle analysis (LCA) and other calculations (e.g., Cady, 2020; Ridoutt, 2021a, b; Blignaut *et al*., 2022). It is recognised that these arguments and calculations as yet are not well accepted in the scientific community, but they do suggest that there is sufficient evidence that calculations through GWP100 may be overestimated.

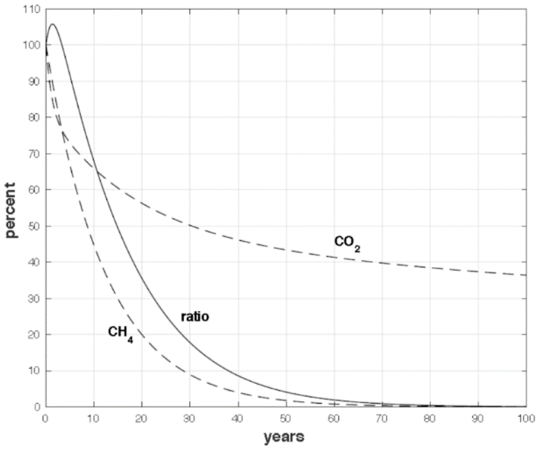

Figure 2 The persistence of carbon dioxide and methane in the atmosphere as a function of time
Note: The chart begins when a pulse of the gas is injected into the atmosphere. The legacy effect of methane is miniscule compared to that of carbon dioxide.
Source: Muller & Muller (2017)

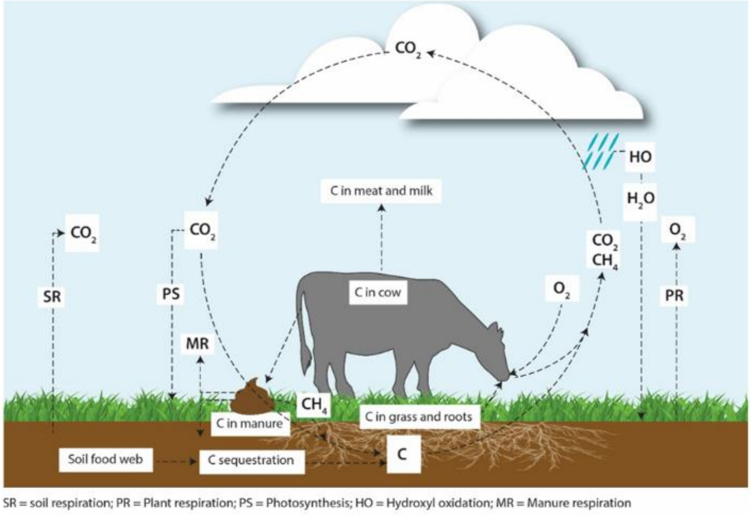

Figure 3 The biogenic carbon pathway

The biogenic carbon pathway (Figure 3) illustrates the integral role of cattle in drawing CO_2 from the atmosphere through photosynthesis, the carbon of which is sequestered into plants and roots and is then captured in the soil. Methane from the cow is oxidised in the atmosphere by hydroxyl oxidation and other substances to CO_2. In contrast to the CH_4–CO_2 relatively stable relationship in the biogenic carbon pathway which has evolved over millions of years between rangelands and herbivores (Figure 3), the entrance of CH_4 into the atmosphere from fossil fuel origin, peat, and CH_4 trapped beneath ice masses in the polar regions – and now being released due to global warming – is ‘new’ to the atmosphere and results in accumulation because the rate of removal is exceeded (Mitloehner, 2020).

With respect to enteric CH_4, from results of calorimetry trials on a wide range of forages and forages plus supplements in Australia, Charmley *et al*. (2016) regressed methane production on gross energy intake (GEI). These Australian forages correspond to forages and forages plus supplements used in many countries in the world. The prediction equation has a R^2 of 0.93 and the estimate of methane production was 6.3% of GEI. This resulted in a mean relationship of metabolizable energy (ME) equal to 0.905 digestible energy (DE) instead of the usually accepted relationship of ME = 0.82DE (Hales, 2019). The results of Charmley *et al*. (2016) are supported by a dataset from calorimetry trials with dairy cattle and growing steers used in comparing model predictions (Kass *et al*., 2022), where enteric methane was only 4.75% of digestible organic matter (DOM) at dietary DOM of 55% and 2.2% at a DOM of 84%.

The last pathway accounts for the GHG emissions inclusive of the contribution of the animal being a carbon sink and not just a source of emissions. Currently, carbon accounting focuses almost exclusively on enteric and manure-based CH_4 emissions. The fact that livestock production also contributes to the sequestration of carbon is largely ignored. It is assumed that, in addition to enteric emissions, the carbon absorbed by the animal in the form of feedstock is oxidised and returned to the atmosphere. An important omission in carbon footprint assessments is the carbon cycles within the animal to enable physiological functions of maintenance, pregnancy, lactation, and growth. The within-animal pool (Figure 3) completes the carbon cycle and needs to be considered as well (Mitloehner, 2020; Blignaut *et al*., 2022). This within-animal carbon pool should be considered as a virtual carbon sink (Atkinson *et al*., 2011; Chen *et al*., 2020; Blignaut *et al*., 2022).

The arguments above provide significant evidence that, on average, the GWP of CH_4 in the atmosphere may be lower than until recently accepted if the implications of GMP* are accepted. Global cattle CH_4 emissions (if Tier 2 calculated), should also be much lower towards 2050 than accepted in the literature for LCA calculations due to the cattle number arguments above; the lower enteric CH_4 production, as shown by Charmley *et al*. (2016) and Kass *et al*. (2022); proof of a virtual carbon sink (Atkinson *et al*., 2011; Chen *et al*., 2020; Blignaut *et al*., 2022); and proof that in many countries, the same productivity is maintained with less cattle than in the past (Capper, 2011a, b; Capper & Cady, 2020). In fact, the evidence of a slowing down (even reduction) of cattle numbers towards 2050 as suggested earlier, may even result in a cooling down of the cattle-induced CH_4 in the atmosphere, if the predicted outcomes of GWP* and the reasoning of Mitloehner (2020) about fossil and other earth sources of CH_4 as being new to the atmosphere, are accepted.

Nitrous oxide

The relationship between cattle and nitrous oxide (N_2O) is primarily indirect through their feed stocks. Nitrous oxide is emitted in comparatively small quantities from cattle manure and primarily following chemical N fertilisation and pesticide application of crops, cover crops, and cultivated pastures. As chemical fertilisers, N application to agricultural crops has increased dramatically, from 10 Tg N/ha in 1961 to 77 Tg N/ha in 2016 (Elrys *et al*., 2020; Martínez-Dalmau *et al*., 2021). Nearly half of the N fertiliser supplied is not used by crops and is lost to the ecosystem through volatilisation, runoff, or leaching (Billen *et al*., 2013). These losses may lead to environmental pollution, such as the release of GHGs, negative infiltration of aquatic water bodies (Martinez-Dalmau *et al*., 2021), soil acidification, and biodiversity reduction. For example, due to the low N-use efficiency of the crops and the extreme mobility of the reactive forms of N in either the gas or the soluble phase, the excess N applied has a high risk of being lost to the environment (Sahrawat, 1982; Tubiello *et al*., 2013).

Nitrogen is released into the atmosphere during the processes of de-nitrification (reduction of NO_3^- to N_2 by soil microbes) under anaerobic conditions, and nitrification (oxidation from NH_4^+ to NO_3^-) under aerobic conditions. The atmospheric level of N pollution by 2050 is expected to be in the range of 102–156% higher than in 2010, with the agricultural sector accounting for 60% of this increase (Bodirsky *et al*., 2014; Martinez-Dalmau *et al*., 2021). The lifespan of N_2O in the atmosphere is 110–120 years and its GWP is 298 times that of CO_2 at GWP100, i.e., exactly as calculated by the IPCC over the 100-year period. Thus, although N_2O concentration in the atmosphere is only 1/1 000 of CO_2, it is 5–6% of all GHG in the atmosphere and increasing at a rate of 0.25% per year (Crutzen *et al*., 2008). In 2018, N_2O emissions from agriculture to the atmosphere were 7.718 Gg (FAO, 2018). Thus, its warming effect is substantial and increasing. In addition, N_2O is one of the ozone-depleting substances in the atmosphere (Ravishankara *et al*., 2009).

The implications are that agricultural practices need to limit N fertilisation and other chemical substance applications. Currently, the status is that developing countries remain in the phase of increasing N pollution (e.g., India), certain countries are in the transition phase (e.g., China), while others are in a phase of reducing pollution (e.g., the USA and the EU) (Zhang *et al*., 2015; Martinez-

Dalmau *et al*., 2021). To limit pollution by N_2O, practices of conservation and regenerative agriculture (CA and RA) in crop production should be implemented, which are discussed in the following sections. In these practices, cattle play a significant role. One aspect is the supply of organic N through manure as substitute for chemical N fertilisation.

Soils and carbon stocks

Livestock production can be a direct (or on-site) force, such that increasing the number and frequency of grazing animals may lead to changes in soil health. Excessive or poor grazing management causes soil compaction and erosion, decreased soil fertility and water infiltration, and a loss in soil organic matter content and water storage capacity. On the other hand, the total absence of grazing also reduces biodiversity because of the invasion of less desirable plant species and bush encroachment. Good grazing practices and trampling can stimulate grass tillering, improve seed germination and biodiversity, and improve soil health (De Haan *et al*., 1997).

Soil is involved in the biogeochemical cycles of C and N, and thus is key to climate regulation, either by emitting GHGs or by sequestering C. By sequestration, soil can store vast amounts of C: globally the few first meters of mineral soils contain 1 500–2 400 Pg of organic C (Ciais *et al*., 2013; Stockmann *et al*., 2013). This is approximately three to four times the amount of C in vegetation (450–650 PgC) and 2–3 times the amount in the atmosphere (~829 GtC) (Bispo *et al*., 2017).

Fargione *et al*. (2018) quantified the potential of natural climate solutions (defined as conservation, restoration, and improved land management interventions on natural and agricultural lands) to increase carbon storage and avoid GHG emissions in the US. They showed the potential as being 1.2 ± 0.3 Pg CO_2 e per year, which is the equivalent of 21% of the total net annual emissions of the US. In a similar study, Griscom *et al*. (2017) estimated that natural climate solutions can provide 37% of cost-effective CO_2 mitigation required by 2030 for a >66% chance of holding global warming to below 2 ^{o}C. Even though the potential of soil carbon accumulation is dependent on soil type (much less in sandy than in clay soils) and accumulation does reach a plateau (Miles, 2022), the potential for carbon removal from the atmosphere and storage in soil over the short to medium term is clearly substantial. In this, agricultural practices need to play a significant role. The role of cattle (and other herbivores) is through its essential link in the biogenic carbon cycle which channels carbon through the plant to the soil (Figure 3).

Associations with rangeland

Rangelands contain a broad variety of plant species for wild and domestic herbivores. Of this, grasslands, shrublands, and savannahs are the most important in livestock production and cover approximately half of the world's terrestrial surface with some of the most diverse ecosystems on Earth. Humans have always played an important role in maintaining, cultivating, and managing these areas through planned fires, hunter-gathering, and pastoralism. Livestock play a key role in reducing biomass loads, moving around nutrients, trampling and breaking crusted soil surfaces, improving soil infiltration, and increasing diversity. Not only is carbon stored in vegetation above the earth's surface, but there are also significant amounts in roots and tubers below ground and in the soil itself (Sacande *et al*., 2020).

Taken together, grasslands cover 3.67 million km^2, which is 46% of all global rangeland types and it co-evolved with herbivores, soil biota, and predators (Retallack, 2013). The grasslands are one of the world's most extensive terrestrial biomes, covering more than 40% of the terrestrial surface of the earth (Hewins *et al*., 2018) and are central to the survival of modern-day livestock herbivores, their associated pastoralists, and commercial farmers, in addition to a diverse community of large wild mammals (Marshall *et al*., 2018; Bond *et al*., 2019), the African continent being a prominent example where countless wild herbivores still graze, such as in the Serengeti–Masai Mara complex. Although cattle habituate most biomes, the grasslands are the major home of cattle on all continents. India and some neighbouring countries are unique since significant numbers are kept in urban areas because of social, cultural, and religious orientations.

The grassland biome is also an extremely important resource for soil carbon sequestration, even more than forests (Bond & Zaloumis, 2016; Silveira *et al*., 2020). Furthermore, it is important because many arid and semi-arid grass species have co-evolved with herbivores (Hendrickson & Olson 2006; Weber & Horst, 2011), thereby indicating the important role which cattle as the major herbivore in contemporary times must play in the quest to mitigate climate change, and to use and protect grasslands, and of course, other rangelands that they inhabit.

There is a growing amount of evidence that GHG emissions associated with rangelands are primarily due to poor grazing management, resulting in either inadequate use or bare ground and soil erosion (Schuman *et al*., 2002; Gosnell *et al*., 2020), and that managing grazing effectively can, in fact, contribute to CO_2 removal from the atmosphere by enhancing soil carbon sequestration (Teague *et al*., 2011; Stanley *et al*., 2018). In this context, Hewins *et al*. (2018) demonstrated that moderate grazing enhanced soil organic carbon (SOC) in the upper 15 cm by 12%, compared with no grazing. One explanation is that plants put more carbon below ground because of grazing than plants not grazed by increasing root mass up to three times more in grazed grasslands than in ungrazed grasslands (Nickel, 2021). The response of plant roots to grazing is to produce more roots and exudate through the roots which feed the microbial population, thereby also improving soil health.

Effective grazing management requires some form of rotation as it is generally accepted that perennial (even annual) grasses require recovery periods after grazing to produce and develop new tillers and root systems and replace nutrients lost in grazed tissue (Fynn *et al*., 2017). Rotational grazing requires multi-paddocks through which livestock herbivores (cattle) are rotated in one or more cycles during a season. While there are differences of opinion regarding the intensity of grazing (Chamane *et al*., 2017; Franke *et al*., 2022; Hawkins *et al*., 2017; 2022), relatively high to ultra-high density, quick rotation systems have shown increasing interest. These systems may advance photosynthesis and promote soil cover if correctly applied (Savory & Butterfeld, 2016; Fynn *et al*., 2017; Gosnell *et al*., 2020; Teague & Kreuter, 2020; Spratt *et al*., 2021). They may also enhance root and soil microbial mass as an additional benefit, but this depends on the biome (Franke *et al*., 2022).

The grazing management system adopted should ensure high forage plant biomass (dead litter or living plants) as permanent soil cover, which is highly effective in reducing soil erosion; livestock consuming grazed forages under appropriate management will result in more carbon sequestration than emissions (Teague *et al*., 2016; Shresta *et al*., 2020; Teague & Kreuter, 2020). Regeneratively grazed pastures maintain dense, diverse stands of living plants, which in addition to preventing erosion, can improve soil fertility and reduce nutrient runoff due to increased water infiltration (Park *et al*., 2017). Perennial pasture under regenerative management also improves water quality (Dinnes *et al*., 2002); promotes healthy soils that can absorb heavy rains, thereby mitigating nutrient and sediment runoff, downstream flooding, and drought (Basche & DeLonge, 2019; Spratt *et al*., 2021); and increases soil water storage capacity through organic matter accrual (Rawls *et al*., 2003). It is clear that the benefits of cattle to carbon sequestration by effective grazing management is of a magnitude that can exceed GHG reductions by reducing cattle numbers as proposed by Ripple *et al*. (2014), which therefore should be the preferred policy because of all the benefits to the environment and society at large, as described above.

The improper utilization and management of rangelands and consequent land degradation, however, continues unabated in some parts of the world, especially in arid, semi-arid, and sub-tropical rangelands of Africa (Liniger & Mekdaschi Studer, 2019). Climate change and weather variability in the past decades have worsened the situation. Restoration efforts in these mostly complex situations are difficult and call for the research and development of well-adapted livestock and grazing management practices (Savory & Butterfeld, 2016; Ng'ang'a *et al*., 2020) to improve the natural resources, income, and livelihood of agro-pastoralists.

Associations with crops

In mixed farming systems, crop and livestock production are done on the same farm. The full integration of livestock with cropping systems, usually referred to as Integrated Crop–Livestock Systems (IC–LS), has been a foundation of agriculture for hundreds of years (FAO, 2010). Regionally, the mixed farming systems of the Organisation for Economic Co-operation and Development (OECD) countries and Asia provide by far the largest share of these practices, but also in sub-Saharan Africa, West Asia and North Africa and Central and South America, mixed farming is the main system for smallholder farmers (De Haan *et al*., 1997).

According to the FAO (2010), mixed production systems currently generate close to 50% of the world's cereals and most of the staples consumed by poor people. They also produce the bulk of livestock products in the developing world (75% of the milk and 60% of the meat) and employ many millions of people on farms, formal and informal markets, processing plants, and other components of long value chains.

In recent decades, the integration of livestock with conservation agriculture cropping systems was perhaps among the most significant innovations in these mixed production systems to ensure economic and ecological sustainability and resilience, while providing ecosystem services, such as increased biological diversity, nutrient cycling, and improved soil health. It also enhances forest preservation and contributes to adaptation and mitigation of climate change. Within the economic and production dimension, sustainable IC–LS enhance livelihood diversification and, potentially, efficiency through optimization of production inputs including labour, offering resilience to economic stresses, and reducing risks.

Resource use in mixed farming can be highly self-reliant as nutrients and energy flow from crops to livestock and back. By definition, such a closed, fully integrated IC–LS offers positive incentives to compensate for environmental effects ("internalize the environmental costs"), making them less damaging or more beneficial to the natural resource base (De Haan *et al*., 1997).

As discussed above, one of the most significant solutions to the problem of global warming and climate change is to draw down, or sequester, atmospheric CO_2 back into soil and other biotic pools through photosynthesis. This is a critical intervention to increase SOC levels beyond a threshold level of ~1.2% in the surface layer and 1.1–1.5% in the root zone (Lal, 2009), which will improve soil health, increase agronomic productivity, and protect the quality of water resources. Over-tilled or degraded soils generally contain much lower levels of SOC and cannot perform these essential ecosystem functions and services. Further indicators are an improvement of 1% carbon in the upper 30 cm of the soil, which will coincide with the addition of 25 kg atmospheric N; for each 1% increase in soil organic matter (SOM), soil water holding capacity will be increased by 16–250 kℓ/ha/year (the variation depends on soil type and land area) (Hudson, 1994).

In croplands, no-till practices therefore offer promising options towards adaptation and mitigation of climate change. The addition of innovative and diverse cropping systems through crop rotations, sequences, associations, and cover crops in RA and CA practices can have further benefits. However, the integration of livestock through the inclusion and grazing of cover crops on the croplands has been proven as one of the most significant contributions in IC–LS. Kaye & Quemada (2017) reported that cover crop effects on GHG fluxes mitigated warming by ~100–150 g CO_2e/m^2/year, which is higher than mitigation from transitioning to no-till. The most important factors were soil carbon sequestration and reduced fertiliser use, with an additional advantage if legumes were used in cover crop systems. Maximum benefits can be obtained if the full range of RA tenets are included. Lal (2020) commented: “RA comprises system-based conservation agriculture (CA), which includes no-till farming in conjunction with residue mulching, cover cropping, integrated nutrient and pest management, complex rotations, and integration of crops with trees and livestock.” The multiple benefits achieved through the integration of the different tenets of RA are supported by research and farmer experiences across the world (Branca *et al*., 2011; Kassam *et al*., 2018; Mitchell *et al*., 2019; Hancock Natural Resource Group, 2020; Kassam, 2020; Larbodière *et al*., 2020). Some of the different tenets of RA systems are shown in Figure 4.

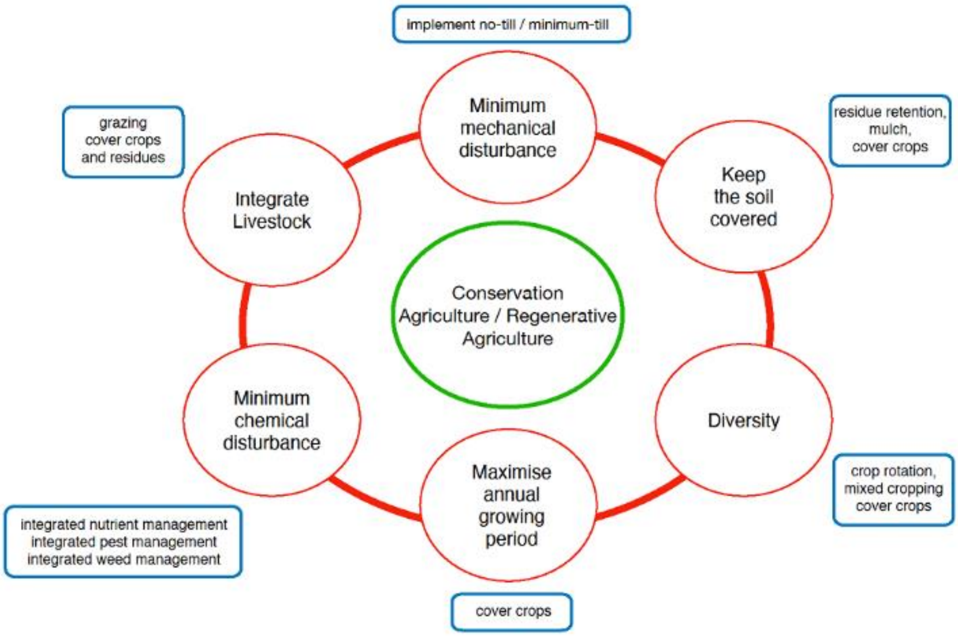

Figure 4 Basic tenets of regenerative agriculture designed to draw carbon dioxide from the atmosphere

As mentioned above and shown in Figure 4, in mixed farming systems, livestock integration (or IC–LS) through crops (and trees where applicable) is a key component of RA systems. Grazing certain crops (e.g., cover crops) or crop residue with cattle (and other livestock) adds to the benefits of the described RA practices. In this regard, two reviews are of significance. Teague *et al*. (2016) concluded: "Incorporating forages and ruminants into regeneratively managed agroecosystems can elevate soil organic C, improve soil ecological function by minimizing the damage of tillage and inorganic fertilizers and biocides, and enhance biodiversity and wildlife habitat, and to ensure long-term sustainability and ecological resilience of agroecosystems, agricultural production should be guided by policies and regenerative management protocols that include ruminant grazing." Brewer & Gaudin (2020) concurred by arguing that livestock re-integration holds notable potential to increase cropland SOC through controls on landscape net primary productivity, allocation of biomass below ground, efficient recycling of residual crop nutrients, an increase in photosynthetic capacity, and soil biological activity related to a suite of soil ecosystem services. In integrated crop–cattle systems with crop residues and multi-species cover crops, more cattle numbers than normal can be used in comparatively high-density rotational management practices because of high plant biomass, to the benefit of photosynthesis, soil health, productivity, and economic outcomes of the enterprise.

Greenhouse gas emissions from intensive beef production systems

Intensification of production has been explored as one way of limiting the increasing pressure on natural resources to improve productivity and efficiency of global beef production systems (Greenwood, 2021). Practices, such as feedlotting, that improve growth efficiency and take-off rates of cattle, contribute to sustainability and food security (Pelletier *et al*., 2010; Capper & Hayes, 2012; Greenwood, 2021), and since feedlot finishing reduces time spent in finishing, it is expected that emissions from enteric fermentation and manure from this production phase will be less than in less-intensive systems, such as from pastures. This has been substantiated by Phetteplace *et al*. (2001), who showed that pasture-finished beef (19.2 kg CO_2-e/kg) from managed grazing systems emitted more greenhouse gases compared to feedlot-finished beef (14.8 kg CO_2-e/kg) when evaluated from an equal live-weight production basis. Apart from turnover rate, other reasons are higher quality (concentrate) diets and increased growth rates, which reduce overall ruminant methane and manure nitrous oxide emissions (Lovett *et al*., 2005; Casey & Holden, 2006; Hyslop, 2008), and metabolic modifiers which may reduce enteric methane by up to 15% (Cooprider *et al*., 2011).

As in other production systems, the feedlot phase is but one of the phases in the system. According to the USDA (2015), 70% of the carbon footprint in a production system is produced during the cow–calf phase, followed by 13% during the stocker or backgrounding phase (primarily on pasture), and 17% of the carbon footprint is produced during the feedlot finisher phase. This implies that (a) the overall gain in emission reduction by feedlotting compared to other production systems is comparatively small, and (b) that efforts of mitigation should primarily target the cow–calf and stocker phase, where carbon sequestration provides the major opportunity as discussed above, while not neglecting emission reduction *per se*. In many instances, cattle reproduction rates are less than optimal, resulting in more animals in the cow–calf phase that of necessity consume lower quality, forage-based diets, which will result in higher daily methane yields per animal (Yan *et al*., 2006; Van der Westhuizen *et al*., 2020; Greenwood, 2021). If, however, grazing intensity can be manipulated such as with high intensity grazing discussed above, the quality of the diet during the cow–calf phase can be improved. Phetteplace *et al*. (2001) found that transition to intensive grazing during the cow–calf phase, as opposed to less management-intensive grazing, can reduce emissions, and DeRamus *et al*. (2003) reported that best management (rotational) practices in grazing systems could reduce enteric methane emissions by as much as 22% compared to continuous grazing. As a further adjunct, more intensive finishing systems, such as with concentrate supplementation and feedlotting, can help to maintain beef production and reproduction rates during periods of drought or when forage availability is inadequate by reducing the stocking load on the rangeland and supplying the required nutrients, in addition to reducing enteric methane.

Observations and conclusions

The purpose of this investigation was to evaluate the risk to the global socio-economy and the environment if cattle production increases towards 2050, according to projected needs and demands of the global economy. The following observations and conclusions are pertinent:

- Estimations of global and country cattle numbers vary considerably between literature sources. In addition, expectations of numbers towards 2050 are unrealistic, which are of concern as projections of needs, future production, and trade will not realise. Projections indicate stagnation and possibly a decrease in cattle foods, at least per capita.

- Livestock provide over half of the global agricultural output and current world trade is healthy. Cattle, in addition to being a source of food, provide several essential socio-economic services in the developing world that cannot be replaced.
- Consumption of animal-based foods is rapidly increasing in developing and transition countries and yet, is still much below consumption in developed countries. The low consumption in poor countries is a major reason for nutritive imbalances, stunting, and low cognitive development as animal-based foods are nutrient dense in contrast to plant-based foods, which alone can rarely meet nutrient requirements.
- Although the literature is contradictory, there are very few meta-analysed studies that show negative relationships between animal-based foods and cardiovascular diseases and cancer. It is rather a case of quantity resulting in obesity and insulin resistance.
- Methane emissions by cattle are much lower than previously accepted because global cattle numbers are much lower than estimated, the global warming potential of CH_4 has apparently been over-estimated, the relationship with the biogenic carbon pathway has not been understood, and how it is affected by the physiological function of the animal is undetermined. Furthermore, the effect of additional soil carbon resulting from the manure is generally ignored.
- Nitrous oxide is a dangerous polluter in the atmosphere. In agriculture, it is primarily derived from chemical fertilisation during crop and pasture cultivation, which is also damaging to soil health. These practices should be limited and organic sources, such as animal (cattle) manure and compost, should be used.
- Grasslands constitute 46% of rangeland surfaces, have co-evolved with herbivores, and are the largest source of photosynthesis and carbon sinks into soil, even larger than forests. The implication is that this resource and its herbivore grazers (cattle being the prime example) need to be protected against degradation at all costs through well-adapted livestock grazing systems in different contexts.
- Photosynthesis, carbon sequestration, and soil health should be emphasised in rangeland management, using quick rotation and comparatively high-density grazing practices with cattle where feasible; and in integrated crop–livestock systems, by introducing multi-species cover crops and livestock grazing, and/or employing feedlotting as an alternative. This will accommodate more animals per unit of land for the benefit of healthy ecosystems, productivity, and economic returns.
- Livestock forms an integral part of regenerative agriculture systems leading to multiple environmental, social, and economic benefits, with soil health at the centre. The research and development of well-adapted and adopted livestock and grazing management practices using CA principles in different local contexts are key.
- Finally, there is very little evidence of socio-economic and environmental risk if cattle production is to be increased towards 2050, provided a number of influencing factors are addressed, such as resource degradation and the implementation and scaling out of sound grazing management practices. For the developing world, an increase in cattle foods will be mostly beneficial. However, cattle number and production trends do not predict an increase, which points to further increases in pork and chicken to meet future demands for animal-based foods.

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Authors' contributions

HHM initiated and conceptualised the manuscript and was responsible for most of the writing, JNB was jointly responsible for the data compilation and the socio-economic component, HJS was jointly responsible for the environmental component, and CJLduT was jointly responsible for the livestock component and its relevant data manipulation.

Conflict of interest

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Annexure 1: Growth in the cattle population, production, and yield over time according to the FAO (2021)

According to the FAO, the number of cattle increased steadily from ~950 million animals to more than 1,4 billion from 1960 to 2020 (Figure A1(A); FAOSTAT, 2021). The polynomial relationship has a higher R^2 (0.9727) than the linear relationship ($R^2 = 0.9485$), which suggests that the cattle numbers have been increasing at a declining rate. Likewise for the yield growth (Figure A1(B)) that increased from approximately 160 kg/carcass to 220 kg/carcass with the polynomial function having a higher R^2, suggesting an increase at a decreasing rate. The combined impact of the yield increase and the increase in the herd has led to an increase in production (Figure A1(B)) from approximately 28 million tonnes to 68 million tons, an average growth rate of 1,57% per year.

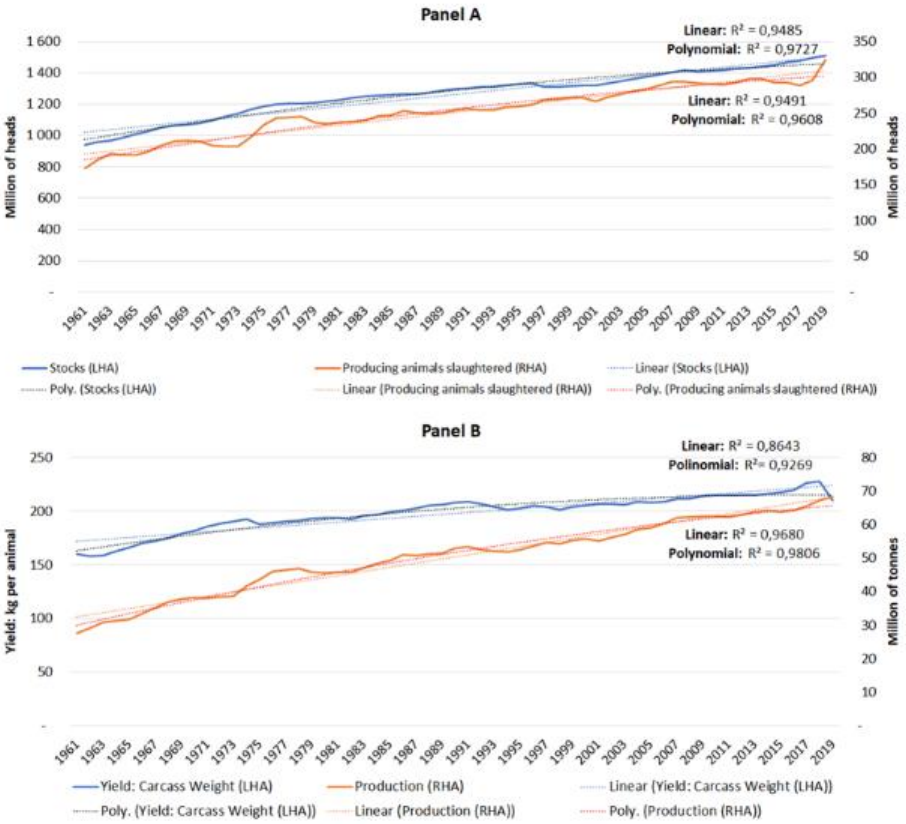

Figure A1 Global cattle statistics: Stocks and animals slaughtered (Panel A) and carcass yields and production (Panel B) between 1961 and 2019 and its linear and polynomial relationships
Source: Data from FAOSTAT (2021)

Regression equations:
Panel A:
Linear: Stocks (million)(Y) = 8.327 (years post 1960)(X) +1014; Polynomial: $-0.087X^2 + 13\ 57X + 961$
Linear: Animals slaughtered (million)(Y) = 0.616 (years post 1960) (X) + 31.98; Polynomial: $-0.004X^2 + 0.893X + 29.16$
Panel B:
Linear: Production (million tons) (Y) = 2.019 (years post 1960) (X) + 191; Polynomial: $-0.015X^2 + 2.902X + 182$
Linear: Carcass weight (kg) (Y) = 0.903 (years post 1960) (X) + 171; Polynomial: $Y = -0.016X^2 + 1.859X + 162$

Annexure 2: Cattle population of Brazil, India, China, and Russia from various sources

The cattle population according to various sources for Brazil, India, China, and Russia is depicted in Table A1.

Table A1 Cattle population (million) of selected countries and global totals, as compiled from various sources

Country	Reference	2009	2012	2013	2014	2015	2016	2017	2018	2019	2020
Brazil	WDA[1]		203	208	213	219	226	232	238	244	253
	FAOSTATS[2]	205		187			218		214		
	Statista[3]						218		214	215	
	WCP[4]				212			215			
India	FAOSTATS	196		195			186		185		
	Vikaspedia[5]		191							193	
	WCP				189			185			
China	WDA		91.4	89.9	90.1	90.6	88.3	90.4	89.2	91.4	95.6
	FAOSTATS	82.6		103			84.5		63.4		
	WCP				114			83.2			
Russia	WDA		19.7	19.3	18.9	18.5	18.2	18.2	18.1	18	17.9
	FAOSTATS	21		28.7			19		18.3		
	WCP				19.9			18.8			

1 – WDA (World Data Atlas) (2020); 2 – FAOSTATS (2020); 3 – Statista (2021a); 4 – WCP (World Cattle Population) (2019); 5 – Vikaspedia (2019)

Table A2 Other countries with comparatively large cattle populations (>20 million head); averages of different sources

Country	**2009**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
United States	94.7	90.1	92.6	89.3	91.9	92.8	94.0	94.6	94.3	94.0
EU*		77.8	78.6	80.1	80.9	80.9	79.0	77.8	77.2	76.5
Ethiopia	50.9		55.0	54.0		59.5	60.9	62.6	61.5	
Argentina	54.5	52.2	52.5	51.7	53.1	53.4	54.1	54.5	54.5	53.8
Sudan				41.9			30.7			
Pakistan	33.0		36.0	38.3		42.8	44.4	46.1		
Mexico	32.3		31.2	32.4		33.9	31.8	34.8		
Australia	27.9	28.4	28.3	29.2	27.4	25.0	26.2	26.1	23.7	23.2
Tanzania				24.5			26.4			
Bangladesh	23.0		22.8	24.0		23.8	23.9	24.1		
Colombia		21.6	19.9	20.8			22.5			
Nigeria				20.0			20.8			
Total				506.2			514.7			
World-A		1 002	1 005	1 009	969	979	985	990	989	988
World-B		1 427	1 432	1 439	1 452	1 470	1 478	1 494	1 511	

*EU excluding the UK

Sources: De Vaccaro (1977); Rathway (1985); De Alba (1987); Khan *et al*. (1999); Otte & Chilonda (2002); Arelovich *et al*. (2011); FAOSTATS (2018); World Cattle Population (2019); Abay & Jensen (2020); World Data Atlas (2020); Cattle Industry (2021); Ethiopia NDC Report (2021); Eurostat (2021a); USDA (2021); World-A – Shahbandeh (2021); World-B – FAOSTAT (2021)