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Review: An overview of beef production from pasture and feedlot globally, as demand for beef and the need for sustainable practices increase

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ABSTRACT

Beef is a high-quality source of protein that also can provide highly desirable eating experiences, and demand is increasing globally. Sustainability of beef industries requires high on-farm efficiency and productivity, and efficient value-chains that reward achievement of target-market specifications. These factors also contribute to reduced environmental and animal welfare impacts necessary for provenance and social licence to operate. This review provides an overview of beef industries, beef production, and beef production systems globally, including more productive and efficient industries, systems and practices. Extensive beef production systems typically include pasture-based cow-calf and stocker-backgrounding or grow-out systems, and pasture or feedlot finishing. Cattle in pasture-based systems are subject to high levels of environmental variation to which specific genotypes are better suited. Strategic nutritional supplementation can be provided within these systems to overcome deficiencies in the amount and quality of pasture- or forage-based feed for the breeding herd and for younger offspring prior to a finishing period. More intensive systems can maintain more control over nutrition and the environment and are more typically used for beef and veal from dairy breeds, crosses between beef and dairy breeds, and during finishing of beef cattle to assure product quality and specifications. Cull cows and heifers from beef seedstock and cow-calf operations and dairy enterprises that are mostly sent directly to abattoirs are also important in beef production. Beef production systems that use beef breeds should target appropriate genotypes and high productivity relative to maintenance for the breeding herd and for growing and finishing cattle. This maximizes income and limits input costs particularly feed costs which may be 60% or more of production costs. Digital and other technologies that enable rapid capture and use of environmental and cattle performance data, even within extensive systems, should enhance beef industry productivity, efficiency, animal welfare and sustainability.

Implications

Global population growth and increasing pressure on the environment including land resources will drive improvements in productivity and efficiency of beef production systems. Practices that result in improved reproductive and growth efficiencies and rapid cattle turnoff through more efficient use of feed resources will contribute to this objective. Profitability of beef production systems also requires improvements in achieving target-market specifications using appropriate genotypes and management practices, including for higher-value, premium quality beef production. New measurement technologies notably electronic sensors will enhance development of decision support tools to achieve more sustainable, productive, and profitable beef industries with high standards of cattle welfare.

Introduction

Land areas used in livestock production represent 77% (40 million km^2) of land used for agriculture (51 million km^2) and contributes 18% of global food energy intake and 37% of global food protein supply (Ritchie and Roser, 2020). Population growth and pressures on availability of productive land for livestock production underlie the need for improvements in productivity and efficiency of beef production. Sustainability of beef production requires improved on-farm efficiency and productivity (Capper and Bauman, 2013), and efficient value-chains that reward achievement of target-market specifications. These factors can also

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contribute to reduced environmental and animal welfare impacts necessary for provenance and social licence to operate.

Beef production systems that use beef breeds should target appropriate genotypes and high productivity relative to maintenance for the breeding herd and for growing and finishing cattle to maximize income and to limit input costs, particularly for feed, which may be 60% or more of production costs. Where grasslands or rangelands are the primary source of nutrients, beef production can be sustainably practised. This is particularly so given feed resources within these systems are not suitable for consumption by humans. Dairy cows can also efficiently produce calves for veal and beef due to their milk production while carrying a foetal calf. Hence, they can outperform traditional beef breed systems in relation to productivity, efficiency and climatic impacts due to the level of productive outputs relative to feed resource use and greenhouse gas production. Established and emerging technologies include molecular genotyping, electronic sensors, imaging and wireless networks. Coupled with increasing capacity to rapidly capture, integrate and use data on the environment, cattle performance, and across the supply chain, they should enhance beef industry productivity, efficiency and sustainability, including within extensive systems.

Hence, this review provides an overview of beef production and beef production systems globally in the context of production efficiency and achievement of market specifications. It includes information on factors important for beef production at pasture, in feedlot and within dairy systems, and on some emerging technologies likely to aid in improving productivity and efficiency of beef production and the beef industries globally. The reader should also refer to definitions of terms used in this paper to describe classes of cattle and beef production systems that are provided in Tables 1 and 2.

Overview of global beef production and production systems

There are approximately 1.5 billion head of cattle globally (FAOSTAT, 2020). World demand for beef was 70 million tonnes in 2019 and is projected to increase to 74 million tonnes by 2023. Beef is a high-quality source of protein that provides highly desirable eating experiences. It was the third most consumed meat after poultry (125 tonnes) and pork (118 million tonnes) in 2019. International trade in beef was a record 18% of beef produced in 2019. The major beef producing nations or regions are the USA (17% of beef production), Europe (15%), Brazil (13%), China (9%), Argentina (4%), India (4%), and Australia (4%) (Table 3). The largest beef exporters were Brazil (20% of world beef exports), Australia (16%), India (15% including carabeef from buffalo), USA (13%), New Zealand (6%), Argentina (6%) and Canada (5%) in 2018/9, with the rest of the world supplying about 18% of exported beef (Fig. 1 and Table 3).

The type and scale of beef production systems and supply chains are highly variable between and within major geographic regions and countries. Major beef producing regions that contribute substantially to the global beef trade, notably in North America, South America, and Australia, have more specialized beef cattle production systems in addition to dairy beef production. Beef industries in Europe, New Zealand and India rely heavily on their substantial dairy industries for beef and veal production. Most cow-calf operations within major advanced beef producing regions and countries are pasture-based. South America and Australia have pasture-based systems for growing cattle and finish a substantial proportion of cattle and use pasture for a considerable proportion of cattle for slaughter. North American production systems include a higher proportion of cattle that are feedlot finished for slaughter, although feedlot finishing is increasing in Australia and major South American beef producing nations. Cull cows and heifers from beef seedstock, cow-calf operations, and from dairy enterprises in countries that have large dairy herds are also important for the supply of beef.

In this section, a brief overview of the scale and characteristics of the beef industries within world regions and countries is provided. Most emphasis is on those countries with more advanced beef industries that contribute substantially to global beef consumption and trade.

North America

United States of America

The USA had 94.8 million head of cattle in 2019 and slaughtered 34.3 million head (USDA, 2020). Beef production in the USA totalled 12.3 million tonnes in 2019 making it the largest beef producing nation. Exports were 11.1% or 1.36 million tonnes in 2019. Japan, South Korea, Mexico and Canada were the largest export markets for beef from the USA in 2019. The USA has the heaviest average carcass weight of all beef producing countries (Fig. 2).

The USA spans a wide array of geographic, environmental and agro-climatic zones resulting in the use of many different cattle genotypes and types and scales of production systems (Herring, 2014; Drouillard, 2018). Over 40% of the land area of the contiguous states in the USA is used for beef production. Beef production systems in the USA are predominantly pasture-based, followed by a period of lot-feeding for young steers and heifers destined for market as beef. Typically, there are 30 million or more beef cows with the predominant breeds being Angus, Hereford, Simmental, Red Angus, Charolais, Gelbvieh, Brangus, Limousin, Beefmaster, Shorthorn, and Brahman among 80 or so in the USA (Drouillard, 2018). However, slaughter cattle are mainly crossbred with the majority having some Angus genetics. Some 55% of cows are in the Central region; 20% in the Western region; 20% in the Southeastern region; and 5% in the Northeast, Alaska and Hawaii. The reader is also referred to reviews of USA beef industry by Herring (2014), Drouillard (2018) and USDA (2020).

Cow-calf operations produce weaner steers and heifers, including many cross-bred animals from beef breeds or beef and dairy breeds. Weaners are sent for pasture (stocker cattle) or forage-based feeding in backgrounding dry lots prior to feedlotting (Herring, 2014; Drouillard, 2018). These systems include approximately 60% of weaner calves produced in the USA. Cow-calf operations also produce calves for feedlot production for 240 days or more from weaning. These calves are known as "calf-feds" and represent approximately 40% of beef weaner calves. Backgrounding may also include limit feeding of high-concentrate diets to restrict growth rate and avoid premature fattening prior to feedlot entry.

There are approximately 9.4 million dairy cows in the USA (FAOSTAT, 2020) of which Holstein is the predominant breed. They produce 3–4 million dairy calves for feedlotting each year (Drouillard, 2018). Male dairy calves are typically transported to calf ranches at 3 days of age and are reared in individual stalls to limit spread of disease. These calves are fed milk-replacer, grain and sometimes forage until weaning at 40 to 80 days of age. They are then group-fed until 150 to 200 kg and sold to feedlots (Herring, 2014; Drouillard, 2018). As in Europe (see below), dairy females are increasingly being inseminated with sexed semen including beef breed semen to produce males destined for beef production.

Most culled beef cattle from seedstock and cow-calf operations and culled dairy cattle are sent directly to slaughter for meat. However, some culled animals may enter feedlots for 50 to 100 days to fatten prior to slaughter depending on economics (Drouillard, 2018). Dairy enterprises in the USA typically cull almost 30% of their dairy cows annually (Edwards et al., 2019).

Table 1
Brief description of classes of cattle used in beef production, including synonyms and sub-categories.

Class of cattle	Description
Calf	Young bovine with no permanent incisor teeth, can be a male or a female with no secondary sex characteristics.
Bobby calf	A calf that has been removed from its mother. In the case of a dairy cow, this generally happens when the calf is only a few days old, so it does not deplete the cow's milk supply.
Vealer	Calf with no evidence of eruption of permanent incisor teeth. Typically, not weaned for more than seven days. Exclusively or primarily fed milk for bobby calf, white veal or rosé veal production.
Weaner	A young animal that has been weaned from its mother's milk to live completely on pasture or other solid feed.
Calf-fed	Calves feedlot-fed from weaning for 240 days or more.
Yearling	Young, fully weaned bovine without permanent incisor teeth. Animal does not show any secondary sex characteristics. Approximately 12 to 18 months of age.
Heifer	Female bovine that has not produced a calf and is under 42 months of age.
Cow	Mature female bovine used for breeding with eight permanent incisor teeth.
Steer	Castrated male bovine showing no secondary sex characteristics.
Bull	Male bovine with sexual organs intact and that is capable of reproduction. A mature male animal used for breeding.
Backgrounder	Young bovine ready for lot-feeding. In the USA, weaned cattle grown on forage-based diets or limit fed concentrate-based diets in dry lots to feedlot entry weight prior to fattening. In Australia, weaned cattle usually grown on pasture to feedlot entry weight for fattening.
Stocker	Young bovine ready for lot-feeding. In the USA, weaned cattle grown on pasture to feedlot entry weight for fattening.
Finished	Cattle that have reach market specifications and are ready for processing are described as 'finished'. Cattle can be either pasture, forage or grain finished.
Pasture finished	Cattle fattened on high-quality pasture to slaughter specification.
Forage finished	Cattle fattened on forage-based diet such as high-quality pasture, silage or hay to slaughter specification.
Feedlot finished	Cattle fattened on a high energy grain-based diet to slaughter specification. May be described as lot finished, grain finished, lot fattened, grain fattened or feedlot fattened.
Short-fed	Cattle fed on a grain-based diet in a feedlot for a short period of time. Usually refers to cattle that are fed for 50 to 100 days generally for a domestic market that requires leaner beef. May be described as domestic fed or domestic finished.
Long-fed	Cattle fed on a grain-based diet in a feedlot for a longer period of time. Usually refers to cattle that are fed for > 100 days up to 600 days. Includes what may be referred to as medium-fed cattle that are feedlot-fed for 150 to 200 days. Used for supply of marbled beef for export markets such as Japan and Korea, and for hotel, restaurant and institution (HRI) trade. May be described as export fed, export fattened, or export finished.
Cull	Cattle removed or culled from a herd due to factors including age, performance, ill-health, lack of soundness, lack of available feed and economics. May be sent to directly for slaughter, or for short duration finishing prior to slaughter depending on health and soundness.
Purebred	An animal whose parents are of the same breed and may be recorded with a breed registry association.
Crossbred	Animal produced by crossing two breeds.
Synthetic breed	Breed developed from specific crossbreeding programme to create a new breed.
Indigenous breed or genotype	Local or regional long-established or native genotype or breed. Typically well-adapted to the local environment.
Dual-purpose breed	Milk and meat producing breed.
Temperate breed	Breed or type that originates from and is adapted to temperate regions. Includes *Bos Taurus* or taurine cattle, British breeds and European breeds.
Tropical breed	Breed or type that originates from and is adapted to tropical regions. Includes *Bos indicus*, indicine or Zebu cattle, Brahman and Nelore breeds.

Pasture production systems. Cow-calf and stocker-backgrounding beef enterprises in the Central region of the USA make use of the extensive native grasslands (Drouillard, 2018). Beef producers use these pastures in combination with residues from crops, harvested forages, and protein concentrates for cow herds. In the Western region producers typically lease large federally owned grazing areas for spring and summer grazing and use pasture or stored forage such as silage and hay on private lands during winter. Enterprises in the Southeast more commonly use improved pastures within smaller operations.

Feedlotting. Most feedlot operations are in Nebraska, Texas, Kansas, Iowa and Colorado which have ready access to high energy cereal grains, especially corn but also wheat and sorghum, and to grain by-products (Drouillard, 2018). Access to human food by-products has also enabled establishment of feedlots in other areas of the USA such as Washington-Idaho which use wheat and barley as primary energy sources in feedlot diets. Oilseed meals including soybean, cottonseed, sunflower and canola are traditional sources of protein in feedlot diets in the USA. Distiller's grains fed wet or dried and wet corn gluten feed are important cereal by-products. Various by-products can replace at least some of the oilseed meals used to provide additional protein in feedlot diets. Feedlot diets typically include by-products at 40% of the diet. By-products may be included at up to 70% of the diet if economic conditions are favourable. This often increases the protein content of the diet beyond nutritional requirements for finishing cattle (Drouillard, 2018).

Canada

Canada has about 11.5 million head of cattle including 9.5 million beef cattle and 2.0 million dairy cattle. Beef production in Canada ranks twelfth globally, producing 2% or 1.40 million tonnes of beef in 2018. Canada exports 45% of its beef, ranking seventh among beef exporters with 4.8% of world exports in 2019 (Canadian Beef, 2019). The USA (74% of exports), Japan, Hong Kong/Macau, Mexico and China were the major export markets for Canadian beef in 2018.

In western Canada there are 3.7 million beef cows and 2.9 million or 76% of beef cattle finished for slaughter in Canada (Canadian Beef, 2019). Cow-calf operations have about 6.5 million head, feeder and stocker operations 1.6 to 2.2 million head, and feedlots 1.4 to 1.6 million head. Alberta has most beef cows (1.5 million) and the largest average herd size (255 head of cattle), followed by Saskatchewan (1.1 million beef cows, 191 head/producer, respectively) and Manitoba (412 thousand beef cows and 167 head/producer), and the national average herd size is 69 head. Beef production systems in western Canada, where there are the most cattle within Canada, are similar to those in central and western USA. These enterprises are typically cow-calf operations on ranches that produce calves for backgrounding or dry lot, and large feedlots for finishing cattle on high energy concentrate-based diets.

Mexico

Mexico had 16.7 million cattle and slaughtered 6.3 million head from which 2.03 million tonnes of beef were produced in 2019

Table 2
Brief description of systems for beef production.

Production system	Description
Seedstock	Supplier of registered, purebred cattle to multiplier or commercial enterprises. Seedstock cattle have documented pedigrees and estimates of genetic merit, such as expected progeny differences or estimated breeding values.
Multiplier	Producer of offspring from cattle purchased from seedstock herds, usually for supply to commercial enterprises.
Cow-calf	Beef breeding and calf rearing system, also known as suckler herds.
Veal	Calves exclusively or primarily milk feeding for white veal or rosé veal production. Calves with no evidence of eruption of permanent incisor teeth. Typically, not weaned for more than seven days.
Yearling beef	Beef from young, fully weaned cattle without permanent incisor teeth. Animal does not show any secondary sex characteristics. Approximately 12 to 18 months of age.
Backgrounding	Growing programme for feeder cattle from the time calves are weaned until they enter a feedlot to be fattened or finished. In the USA, refers to weaned cattle grown on forage-based diets or limit fed concentrate-based diets in dry lots to feedlot entry weight prior to fattening. In Australia, refers to weaned cattle usually grown on pasture to feedlot entry weight for fattening.
Stocker	Growing programme for feeder cattle from the time calves are weaned until they enter a feedlot to be fattened or finished. In the USA, refers weaned cattle grown on pasture to feedlot entry weight for fattening.
Dairy beef	Weaned dairy cattle grown on forage and/or concentrates to slaughter at ages typically ranging from 12 to 30 months. Includes dairy bull, heifer and steer beef. Can include cattle sired by beef breed bulls mated to dairy females including use of artificial insemination with sexed semen.
Pasture fed	Cattle grown on pasture for manufacturing or lean beef, or for pasture or feedlot fattening. Cattle that have grazed primarily on pastures or crops rather than grains.
Manufacturing beef	System that produces lean, lower eating quality beef used for manufacturing purposes. Also known as commodity beef or grinding beef. Typically uses resilient, lower fatness genotypes, such as tropically adapted cattle, within extensive production systems, and cull cattle.
Pasture finishing	Cattle fattened for slaughter on high-quality pasture or grazed forage crops.
Feedlot finishing	Cattle fattened for slaughter on high energy concentrate-based diets. Where cattle are fed a high energy grain-based diet to reach market specifications.
Marbled beef	System that produces meat with high levels of intramuscular fat known as marbling. Typically uses high marbling genotype cattle and a long feedlot period with high energy concentrate-based diets.
Subsistence	Small-scale family enterprise for self-grown food for consumption to maintain self or family.
Backyard	Small-scale or hobby family enterprise, not usually the primary source of income.
Smallholder	Small-scale enterprise usually family based for food as a primary source of income.
Family	Variable-scale family enterprise often inherited. A primary source of family income.
Corporate	Large-scale organization or company, often horizontally and vertically integrated.
Intensive	Higher input and output per unit land area system. Includes confinement or housed, penned, or fenced enterprise on small land holding, or higher stocking density and productivity grazing enterprise on relatively small land holding that may include irrigation, controlled grazing and grazed or harvested forage crops.
Extensive	Lower input and output per unit land area system. Larger-scale, generally lower stocking density foraging based enterprise including pasture, browse, savanna and/or rangelands.
Forage based	Herbage based including feeding on pasture, browse, savanna or rangelands, or harvested or grazed forage crops.
Pastoral	Pasture-based grazing.
Rangelands	Grasslands, shrublands, woodlands, wetlands and deserts grazed by domestic livestock.
Mixed livestock	Mixed livestock species production system.
Mixed agricultural or agropastoral	Mixed cropping and livestock system.

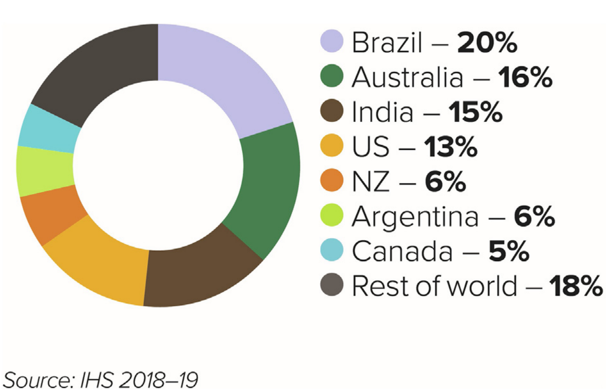

Fig. 1. Share of global beef exports of the major beef producing countries or regions (MLA, 2020a).

(Lara and Kuypers, 2019). Mexico exported 225 thousand tonnes of beef in 2019, the major export markets being the USA, Japan and Korea, respectively. Mexico supplied 19% of total USA beef imports in 2019, making it the third largest supplier to the USA after Canada and Australia.

Beef enterprise types in Mexico have traditionally used *Bos indicus* breeds. Mexico has arid, semi-arid, temperate and humid and dry tropical zones with differing levels and types of beef production systems (Peel et al., 2010 and 2011). Production systems include various cow-calf systems that may also produce live cattle for export, confinement or semi-intensive finishing for domestic production, dual-purpose beef and dairy, and backyard production. Cow-calf systems range from high productivity systems that may use improved and/or irrigated pastures and include improved non-Zebu genotypes for live export to the USA. Cow-calf systems also include semi-intensive systems with somewhat lesser productivity producing beef for domestic consumption, and traditional low productivity systems. The latter two systems also include dual-purpose cattle for meat and milk production. Mexico has a high proportion of small herds. Increasingly, however, confinement, semi-intensive or feedlot finishing of cattle using concentrate-based rations are being used, with sorghum having been used as the primary grain within rations (Peel et al., 2011).

Europe

Europe has a diverse range of beef production systems depending on factors including widely varying agro-climatic regions, the scale of dairy production within regions, and market requirements. Europe has about 119 million head of cattle (FAOSTAT, 2020), of which the European Union (**EU**) had 86 million head in 2019. Of these about 35 million in Europe are dairy cows (FAOSTAT, 2020) or 65% of the European or EU cow herd (MLA, 2020a). Annual European slaughter is about 40 million head producing 10.6 million

Table 3
Summary of production and market characteristics of major beef producing and exporting nations in 2019 (MLA 2020a).

	USA	Brazil	European Union	China	India	Argentina	Australia	Mexico	Canada	New Zealand	Uruguay
Cattle											
Cattle (million head)	95.0	244.1	86.1	87.5	308.7[1]	54.1	26.0	16.9	11.1	10.1	11.4
Dairy % of cow herd	23	43	65	20	100	8	12	31	21	83	7
Cattle and calf slaughter (million head)	34.0	40.6	27.0	50.0	38.8	13.5	8.9	6.3	3.7	4.4	2.3
Cattle exports (million head)	0.27	0.63	0.95	0.02	0	-	1.18	1.35	0.71	0.02	0.15
Beef production and consumption											
Beef and veal production ('000 tonnes cwt[2])	12 289	10 210	7 910	6 850	4 287	3 040	2 397	2 030	1 330	686	568
Total domestic consumption ('000 tonnes cwt)	12 240	8 003	7 905	9 233	2 687	2 360	634	1 880	967	50	137
Domestic share of production (%)	88	78	95	100	63	77	26	83	57	5	17
Per capita domestic consumption ('000 tonnes cwt)	38.2	35.1	15.4	5.4	0.8	56.7	25.0	12.5	25.2	16.8	26.1
Beef exports											
Beef exports ('000 tonnes cwt)	999	1 504	226	-	1 130	436	1 158	225	379	453	335
Chilled % share of exports	44	13	5	2	1	20	26	85	79	7	11
Average export price ($US/kg)	5.61	3.90	4.23	7.02	2.92	5.13	5.54	5.57	7.24	4.93	5.02
Top three export markets	Japan Korea Mexico	China EU Chile	Bosnia and Herzehovia Hong Kong Israel	-	Vietnam Malaysia Iraq	China EU Chile	China Japan USA	USA Japan Korea	USA Japan Hong Kong	China USA Taiwan	China EU USA

[1] Includes 110 million buffalo from which carabeef is produced.
[2] cwt = carcass weight.

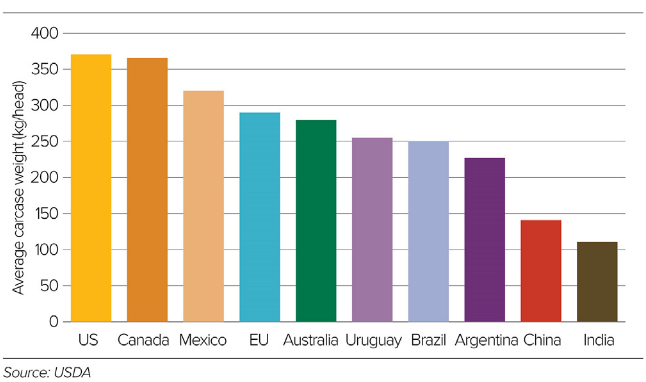

Fig. 2. Average beef carcass weights for major beef producing and exporting nations (MLA 2020a).

tonnes carcass weight equivalent (**cwe**) of beef. The EU had 27 million head producing 7.9 million tonnes cwe of beef in 2019, 95% of which was consumed domestically. The EU's largest beef export markets are Bosnia and Herzegovina, Hong Kong and Israel. A total of 0.95 million live cattle was also exported from the EU in 2019. Compared to other highly developed cattle industries globally, the cost of beef production from beef enterprises in the EU and other European countries can be high, and within the EU may be subsidized. However, the high proportion of beef from dairy herds results in beef production from Europe and the EU being among the most efficient and least polluting in the world (Nguyen et al., 2010; Buleca et al., 2018; Hocquette et al., 2018).

Beef production in Europe is highest in France, Germany, United Kingdom, Italy, Spain and Ireland, respectively (Hocquette et al., 2018). Most European beef is produced as a by-product from dairy farms which have two-thirds of European cattle. Dairy enterprises contribute to white and rosé veal (Skelhorn et al., 2020), finished beef, and beef from culled dairy cattle. More specialized beef farms include cow-calf (suckler) herds and fattening systems (European Commission, 2001; Malau-Aduli and Holman, 2014).

Climate and farming systems are highly variable across Europe and beef production systems depend on available feedstuffs, regional traditions, and markets. European beef production zones can be broadly categorized as Northern mountainous, Northern lowland, Central and the Po Valley, Alpine, and Mediterranean (European Commission, 2001). The Central and Po Valley and Northern Lowland systems are the most highly productive for beef. Breeds include dairy which are predominantly Friesian/Holstein, dual-purpose, and beef. Beef breeds include highly muscled, late-maturing European breeds, earlier maturing British breeds, and local rustic breeds such as in Spain. Dairy cows in some European countries are increasingly being inseminated with beef breed semen, including sexed semen (Pahmeyer and Britz, 2020; Skelhorn et al., 2020). Beef breed sexed semen is more typically used to mate heifers to produce males for intensive feeding and females for pasture-based or lot-feeding systems. These practices allow for better integration of dairy and beef production. They also provide opportunities to rear dairy calves for meat in Europe and elsewhere that would otherwise be killed at birth (Skelhorn et al., 2020).

Milk-fed veal production accounts for about six million calves annually, but a larger proportion of offspring from dairy cows enter beef fattening systems. White veal production mainly uses male dairy calves fed milk-replacer up to 6 months of age (Skelhorn et al., 2020). Rosé veal is mostly produced from male dairy calves up to 12 months of age. They are fed milk-replacer then weaned onto diets with roughage and concentrates (Skelhorn et al., 2020) Dairy calves destined for fattening systems are reared on milk-replacer plus solid feed from 1 to 2 days of age until weaned at 6 to 9 weeks of age. They are then fed forages or forages and concentrates prior to entering systems for fattening (European Commission, 2001).

The major beef fattening systems used in Europe are described in more detail by European Commission (2001). Mainland Europe primarily produces young dairy bull beef fattened for 120–250 days to slaughter at 12–14 months of age, or beef breed bulls weaned at 6–8 months of age and slaughtered at 12–16 months of age. These systems include supply of young beef breed calves for fattening in other counties, for example, 6-month-old weaned calves from beef cows in France that are fattened in Italy. Ireland, the UK and north western France produce steers fattened on grass or fattened indoors on grass silage plus concentrate to 20–30 months of age, and heifers intensively or pasture finished to about 20 months old. Beef production systems that are integrated within cropping systems are more prevalent in central and eastern European countries (Zjalic et al., 2006).

South America

Brazil

Brazil has had the highest rate of growth in beef production of any major beef producing country globally since 2008 and is the world's largest beef exporter (ABIEC, 2019; FAOSTAT, 2020). Brazil had 215 million head of cattle in 2019 which were predominantly *Bos indicus* cattle. Beef production of 11 million tonnes cwe contributed about 9% to its national gross domestic product in 2018 when over 44 million head were slaughtered (ABIEC, 2019). About 80% of beef produced was consumed domestically, and 20% or 2.2 million tonnes cwe was exported in 2018. Brazil has primarily been a supplier of commodity beef and production efficiency is lower than in the USA and Australia. However, productivity in Brazil has been gaining on its major international competitors through improved beef genetics and management and increasing number of feedlot cattle (MLA, 2020a). China was Brazil's largest export market by value in 2018, followed by Hong Kong, EU, Egypt, and Chile.

Cattle numbers in Brazil have increased by 35% since 1998 although they have been relatively stable in recent years (ABIEC, 2019). Brazil's cattle herd is the largest national cattle herd in the world. Numbers of cattle in feedlots have been steadily increasing and accounted for 5.6 million head or 12.6% of the 44.2 million cattle slaughtered in Brazil in 2017. The Midwest is the region with the most cattle in Brazil, followed by the North, Southeast, then Northeast and South regions. There were 2.6 million beef producers in 2017, of which 0.5% had 19.2% of cattle on farms of more than 2 500 hectares, 1.1% had 14.2% of cattle on farms of 1 000–2 500 hectares, 6.6% had 26.9% of cattle on farms of 200–1 000 head, 43.4% had 31.2% of cattle on farms of 20 to 200 head, and 48.4% had 8.5% of cattle less on properties with less than 20 head.

There are about 162 million hectares of pasture lands which is equivalent to 19% of Brazil's 852 million hectares, and an additional 71 million hectares of perennial, semi-perennial and annual agricultural lands (ABIEC, 2019). Of the pastured land, 137 million hectares (84%) is pasture classified as in good condition, 9.7 (6.0%) million ha is pasture requiring recovery, 4.2 million ha (2.6%) is pasture in an advance stage of biological or agricultural deterioration, and 11.8 million hectares (7.3%) includes grain or other crops integrated with livestock. Productivity increased by 176% from 1990 to 2018. During this period, there was an increase in productivity per ha from 24.5 to 67.5 kg beef, and an increase from 4.6 to 11.0 million tonnes of beef production in total. Pastured area in Brazil is reported to have declined from 192 to 162 million hectares between 1990 to 2018 due to reduced deforestation and area under pasture according to ABIEC (2019). However, beef production and deforestation in the Brazilian Amazon has been increasing, with adverse implications for greenhouse gas production and hence climate change (Vale et al., 2019).

Argentina

Argentina ranks tenth among beef exporting countries and produced about 3.0 million tonnes of beef of which it exported 0.58 million tonnes cwe in 2019 (Table 1: Joseph, 2018a). The national cattle herd was 54 million head of mainly *Bos taurus* cattle, and 13.2 million head were slaughtered in 2019 (Table 1). Argentina produces both high-quality and lower quality beef and China, EU, Chile, Israel and Brazil are the largest export markets for Argentinian beef. Increasingly, beef production has shifted from older, heavier cattle to one-year-old cattle (MLA, 2018a).

Grass pastures are the predominant cow-calf feeding and finishing systems which may also include supplementation with grain or silage. Feedlot finishing accounted for 28% of cattle slaughtered in 2016 (MLA, 2018a). Efficiency improvements have not been evident over the past 15 years or so, particularly in cow-calf productivity. This has led to an effort by the Argentinian government through policy support to help industry increase weaning rates through technology, health, genetic and nutritional improvements (Joseph, 2018a; MLA, 2018a).

Uruguay

Uruguay has about 12 million cattle including 4.4 million cows of which 0.33 million were dairy cows. Uruguay slaughtered 2.3 million head in 2019. Total beef production was 0.54 million tonnes cwe and beef exports were 0.42 million tonnes cwe in 2019 making Uruguay the seventh largest beef exporter internationally. Uruguay's major export markets are China, EU, USA, Israel and Brazil (MLA, 2018a and 2020a). Beef production is the major contributor to Uruguay's agribusiness sector.

Cattle are predominantly bred, grown and finished on temperate pasture, but grain finishing is practised for exported beef as well as for live cattle exports of which there were 270 thousand head in 2017. British breed cattle, particularly Hereford that have comprised 65% of the national herd, are most prevalent in Uruguay. Grain-fed cattle represent about 15% of Uruguayan cattle slaughtered, with 80% of grain-fed beef shipped to the EU and 20% consumed domestically. Profitable conditions and expansion of the national herd since 2013 have enabled the Uruguayan beef industry to invest in improved genetics, nutrition and management (Joseph, 2018b; MLA, 2018a).

Paraguay

Paraguay had 13.8 million head of cattle in 2019 on 145 thousand beef producing properties (Meador and Balbi, 2019). Almost two-thirds of the nation's beef cattle are on 4 300 properties, and about 90% of beef producers have less than 100 head of cattle. Beef production is around 0.53 million tonnes cwe of which 0.35 million tonnes is exported, making Paraguay the tenth largest beef exporter globally. Major export markets are Chile, Russia, Taiwan and the EU.

Growth of Paraguay's beef industry is being supported by improved weaning rates in expanding numbers of newer cow-calf operations in the Chaco region. Paraguay has had relatively poor weaning rates due to poor nutrition, reproductive health, and management of cow-calf herds compared to other major South American beef producing countries (Meador and Balbi, 2019). Pasture underpins production systems on ranches in Paraguay, especially in the Chaco and Oriental regions, and 15% or less of cattle are finished for slaughter on grain-based feed. Northern and central Chaco have increased use of Gatton Panic (*Megathyrus maximus var. Maximus 'Gatton Panic'*). Gatton Panic is a variety of Guinea grass that is a deep-rooted clumping grass suitable for inclusion in mixed pasture species swards and is highly productive for all but the winter period in Paraguay. Increasing corn and sorghum grain production in these areas provides opportunity for finishing cattle on grain and silage.

Oceania

Australia

Australia is the world's second largest beef exporter supplying about 16% of beef exported, despite producing only 4% of world beef production (MLA, 2020a). Australia has about 26 million head of cattle of which the dairy herd comprises only 12%. Beef production is about 2.4 million tonnes cwe annually of which about two-thirds is exported. Australia is also the leading long-haul exporter of live cattle globally, and currently exports over one million head each year. Live cattle are primarily sent from Northern Australia to South-East Asia and the Middle East for feedlotting, slaughter or breeding (MLA, 2020a). Australia's major beef export markets are China, Japan and USA, and Indonesia is Australia's most important live cattle market. Beef eating quality standards from Australian cattle grown and finished at pasture or finished in feedlots are assured through Australia's internationally renowned beef quality grading system, Meat Standards Australia (Greenwood et al., 2018).

Beef production systems in Australia are diverse (Bell et al., 2011; Burrow, 2014; Campbell et al., 2014; Greenwood et al., 2018). Pasture or foraging systems encompass northern tropical areas including more coastal, pastoral, and savanna or rangeland regions, arid inland areas, subtropical, and southern warm and cool temperate regions. Most Australian beef production systems are highly seasonal. There are a diverse range of cattle genotypes that include tropically adapted *Bos indicus* Brahman cattle in the harsher more northern regions. Increasingly in northern Australia, crosses with *Bos taurus* breeds including Wagyu and Angus, and other synthetic tropically adapted breeds are being used to improve beef eating quality characteristics, including tenderness and marbling. British, European and Wagyu *Bos taurus* beef breeds, and *Bos taurus* dairy breeds and their crosses, including Wagyu, predominate in more temperate beef production systems. However, tropically adapted genotypes and their crosses with *Bos taurus* breeds are becoming more common in the more extensive subtropical and temperate systems. Similarly, tropical C4 pasture species are increasingly being grown in more temperate areas of Australia. They provide high DM yield but have generally poorer digestibility and nutritional quality than the temperate pasture species.

Northern beef production systems have a distinct wet season that coincides with the warmer months, and a prolonged dry season during the cooler months (Bell et al., 2011; Burrow, 2014; Greenwood et al., 2018). Southern systems have a climate with rainfall predominating during the cooler months and a distinct dry season in the warmer months (Bell et al., 2011; Campbell et al., 2014; Greenwood et al., 2018). Northern systems specialize in beef production on larger holdings, whereas southern beef production includes specialist beef production, mixed livestock, and mixed agricultural enterprises. Rainfall declines towards the more interior parts of Australia, and cattle may be run at very low stocking rates on extremely large properties in the semi-arid zone. Northern systems have mainly produced leaner beef of lower value or live cattle for export, whereas southern systems have mainly produced higher value beef for domestic consumption or export. Northern systems produce more beef than southern systems, but due to different qualities and markets the value of beef production from the north and the south of Australia is approximately equal.

Australia also has a significant beef feedlot industry that has grown over recent decades (Gaughan and Sullivan, 2014). Beef cattle for domestic Australian household consumption enter feedlots to improve the eating quality of relatively lean beef, in which case the periods in feedlot are shorter (<100 days). Cattle genotypes with greater propensity to marble enter feedlots for longer periods (100 to $\geq$350 days, including up to 600 days). They produce more highly marbled, higher value beef which is primarily for export to Japan and Korea and the domestic and export hotel, restaurant and institution (**HRI**) trades. Northern Australian cattle destined for slaughter on arrival in export markets such as Indonesia and Vietnam may also spend time in a feedlot prior to shipment.

New Zealand

New Zealand is an important beef exporting country and almost exclusively produces beef from pasture. There are about 10.1 million head of cattle in New Zealand of which 6.5 million (65%) were dairy cattle and 3.6 million (35%) were beef cattle in 2017 (StatsNZ, 2019). The New Zealand cattle herd is not large by world standards. However, New Zealand exports about 650 thousand tonnes cwe of beef which is 95% of its total beef production of about 680 thousand tonnes cwe. This is the highest proportion of beef for export compared to domestic consumption of any country (Beef + Lamb New Zealand, 2017) and ranks New Zealand fifth among beef exporting countries.

Beef production in New Zealand is largely seasonal from cull adult and young dairy cattle including many grown out on beef and sheep properties. Beef is also produced from more specialized beef producers that use *Bos taurus* breeds such as Angus, Hereford and their crosses that are well suited to New Zealand's temperate environment (Beef + Lamb New Zealand, 2017). About 70% of New Zealand's beef cattle are on the North Island. Beef cattle numbers have declined by about 13% while dairy cattle numbers have increased by 41% over the past 20 years or so. New Zealands major markets for beef are China, USA and Taiwan.

New Zealand is renowned for its highly productive, high-quality temperate pastures. Pasture production in New Zealand is seasonal which contributes to seasonality in the supply of beef (Beef + Lamb New Zealand, 2017). The most productive grazing land in New Zealand has generally been used for dairy cows and heifers and sheep meat production. Specialized beef and sheep production can be complementary or compete for similar land resources including hill farms that are somewhat less productive and more extensive than those for dairying (Bell et al., 2011; Beef + Lamb New Zealand, 2017). Increased numbers of cattle for dairying have also been encroaching on more typical beef and sheep producing areas.

Asia

China

China had 86.5 million head of cattle that produced 6.85 million tonnes cwe of beef from 50 million head slaughtered in 2019 (MLA, 2020a), and demand for beef in China is continuing to grow (Li et al., 2019). About 20% of cattle in China are dairy cattle. Domestic production supplies over 70% of the 9.2 million tonnes of beef consumed, and the widening gap between local supply and demand has resulted in continuing growth in beef imports into China. Imported beef into China is mainly from Brazil, Australia, USA, New Zealand, Argentina and Uruguay (Li et al., 2019; MLA, 2020a).

More than half of beef production in China is from small-scale operations that represent 90% of beef producers, although the numbers of these small-scale producers has been declining since 2003 (Li et al., 2019). These small-scale farmers produce less than 10 head of mainly indigenous breed cattle for slaughter annually, usually in small abattoirs. Most cattle are in intensive cropping regions particularly in the Central Plains and Northeast, with two-thirds of beef production from the agricultural regions (Waldron and Brown, 2014; Li et al., 2019). There are larger grazing herds in more extensive systems in the Northwest, diverse intensive cropping-cattle systems and mountainous grazing systems in the Southwest, and lower numbers in the Southeast. More extensive pasture systems use little supplementation, and crop residues and grains are used to feed cattle in farming regions. Cattle graze during daylight and are intensively housed with crop residue and grain supplements in farming-pastoral regions (Li et al., 2019). Imported cattle from Australia for slaughter and breeding have been enhancing beef production in some regions (Waldron and Brown, 2014; Li et al., 2019). However, limited numbers of young cattle to finish in feedlots has constrained development of the Chinese beef industry, and China has among the lowest average carcass weights of the major beef producing countries (Fig. 2). The reader is referred to the more comprehensive reviews of Chinese beef production and beef industry by Waldron and Brown (2014) and Li et al. (2019).

India

Bovine meat production in India is from cattle, and from buffalo which produce carabeef. India has about 190 million cattle and 110 million buffalo (Kochewad et al., 2017; MLA, 2017b). India's national *bovine* herd of approximately 309 million head is the world's largest (FAOSTAT, 2020). India was projected to produce over six million tonnes cwe of beef in 2020. Of this, 4.3 million tonnes is beef and 2.2 million tonnes is carabeef (MLA, 2020a) but has the lowest average carcass weight of the major beef producing nations (Fig. 2).

Beef and carabeef production in India are mainly by-products of the dairy industry and use of draft animals, and meat supply chains in India are poorly developed compared to other major beef producing countries (Kochewad et al., 2017; MLA, 2017b). Cattle and buffalo are important financially for smallholders and landless labourers. Over 60% of Indian farmers have livestock, with 80% farming on less than 2 hectares (Kochewad et al., 2017). Buffalo meat production has been increasing due to growth and improvements in the Indian dairy industry of which water buffalo comprise about 45% of animals (MLA, 2017b). India exports about one-third of *bovine* meat produced, with Vietnam, Egypt, Malaysia, Indonesia and Saudi Arabia the major export markets. The balance of production is eaten domestically by the 20% of the population who are not Hindu or otherwise vegetarian i.e., mainly Muslims and Christians (MLA, 2017b, 2020a and 2020b).

Japan

Beef production and consumption in Japan has focused mainly on highly marbled beef. Domestic beef production is low by international standards at 324,000 tonnes cwe in 2016, representing 38% of beef consumed in Japan. A further 526,000 tonnes cwe of imported beef was consumed in 2016, with Australia and the USA being the largest suppliers (Gotoh et al., 2018; MLA, 2019a and 2020a). There are about 2.5 million head of beef cattle in Japan of which the Wagyu breeds, predominantly Japanese Black, comprise about 1.6 million head and 0.8 million are either F1-Wagyu-cross or Holstein. Average herd size is about 50 head among the 50 thousand or so specialist beef producers, with producer numbers gradually declining. Dairy and dairy crossbreed cattle average herd size is larger at approximately 250 head per farm (Komatsu and Malau-Aduli, 2014; Gotoh et al., 2018). Cow-calf enterprises have about 15 head per farm and are smaller than fattening enterprises which typically have more than 100 head. Pen feeding using grown forage and imported concentrate feeds is more typical, some imported forages are fed, and 13% or so of beef producers graze cattle (Komatsu and Malau-Aduli, 2014). Beef production in Japan is high cost and low efficiency with relatively small profit margins for producers despite very high retail prices for Japanese beef (Gotoh et al., 2018).

South Korea

Beef production and consumption in Korea is primarily for marbled beef, although there is increasing demand for leaner beef (Chung et al., 2018). There are about 2.6 million head of Hanwoo cattle on about 84 thousand farms in Korea (Chung et al., 2018) from which 277 thousand tonnes cwe of beef was produced in 2016 (MLA, 2017a). Imports of beef have grown from less than 100 thousand tonnes in 1990 to about 400 thousand tonnes in 2018/19, primarily from the USA, Australia and New Zealand (MLA, 2019b). The Hanwoo beef industry in Korea comprises seedstock, multiplier or cow-calf, and feedlot sectors, with many farms having both breeding and feedlot enterprises (Chung et al., 2018). Feed costs are a major issue for Hanwoo beef production, and pasture and corn silage are being used to reduce costs in the southern area of South Korea (Chung et al., 2018).

Indonesia

Demand for beef in Indonesia is growing, and self-sufficiency in beef production is a national priority (MLA, 2018b). Indonesia has about 17 million head of cattle mainly on smallholder farms which supply about 45% of domestic beef consumption. Australian beef and live cattle imports for slaughter or fattening in feedlots contribute to the balance of beef consumed in Indonesia (Agus and Widi, 2018). Indonesian smallholder beef production systems provide meat, manure, draught power and financial assets. Mixed production systems are typical and vary in scale and practices depending on location and land availability (Waldron and Brown, 2014; Agus and Widi, 2018). For example, Javanese producers typically have 2–4 stall-fed cattle on holdings with cropping and livestock, whereas there are herds of 5–50 or more cattle within more extensive systems in other regions or islands with more plentiful land. Smallholder production systems are rudimentary and often keep breeding cattle that produce offspring for sale rather than just having cattle grown for slaughter. Reproduction rates are typically low, and low-quality crop residues which are cheap and abundant and by-products or other non-conventional feeds are fed. Some crossbreeding of local cattle with *Bos taurus* breeds including Simmental and Limousin is practised. Feedlots including large-scale commercial feedlots with associated infrastructure for imported live cattle from northern Australia is practised in West Java and Sumatra Island. Feedlots use by-products from agriculture and industry in their rations to enhance profitability. About 75% of the cattle imported into Indonesia from Australia are 280–350 kg liveweight that enter feedlots, whereas imported finished cattle weighing 400 kg or more are consigned directly to abattoirs (MLA, 2018b; Agus and Widi, 2018). Indonesia has a 5–1 feeder to breeder policy for imported cattle in order to increase local production (MLA, 2018b). Comprehensive reviews of the Indonesian beef industry and beef production systems are provided by Waldron and Brown (2014) and Agus and Widi (2018).

Other south-east Asia

Beef production in other south-east Asian countries mainly comprises small herds of indigenous breed cattle that may have low reproductive rates and some crossbreeding with imported improved breeds. Producers are typically smallholders who feed cattle crop residues, agro-industrial by-products and other non-conventional feeds. Supply chains are less developed than in major beef producing countries. Demand for beef in these countries is increasing and most domestic production is consumed locally. Additional demand may be met by imports including of carabeef from India. Reviews of the beef industries in Thailand (Bunmee et al., 2018) and Laos (Napasirth and Napasirth, 2018) were recently published.

Africa

Africa has 356 million head of cattle including 44 million that were slaughtered in the production of 6.7 million tonnes of beef in 2018 (FAOSTAT, 2020). Most African cattle are in sub-Saharan Africa which covers an area of 22.4 million km^2 and has 700 million hectares of grasslands between the tropics of Cancer and Capricorn (Otte and Chilonda, 2002; Otte et al., 2019). The countries with the largest cattle herds in Africa are Ethiopia (63 million head), Sudan (31 million), Chad (29 million), Tanzania (27 million) Nigeria (21 million) and Kenya (20 million). Uganda, Niger, South Africa, South Sudan, Mali, Madagascar and Burkina Faso each have 10–15 million head (FAOSTAT, 2020). The five main agropastoral regions are Arid (38% of sub-Saharan Africa), Semi-arid (18%), Sub-humid (21%), Humid (18%) and Highland (5%) (Otte and Chilonda, 2002). Livestock production including beef production are important contributors to gross domestic product of sub-Saharan African countries, having roles in the stability of incomes, food supply and farming systems.

Productivity of beef production in sub-Saharan Africa is generally poor and coupled with the growing population has resulted in low per capita consumption of beef and other meats and milk (Otte and Chilonda, 2002; Otte et al., 2019). This is despite Africa undergoing one of the most rapid rates of economic development in the world, and no major decline in the extensive areas covered by grasslands in sub-Saharan Africa (Otte et al., 2019). Beef production in sub-Saharan Africa can be broadly categorized as traditional which includes pastoral, agropastoral and mixed production systems, and non-traditional which includes beef cattle properties or ranches and dairy farms (Otte and Chilonda, 2002). There are a diverse range of indigenous cattle breeds in Africa (Mwai et al., 2015) but traditional systems are characterized by low calving rates, high calf mortality, and low milk production. These factors combine to result in poor production efficiency and limited supply of beef and milk. Poor productivity of traditional systems is a consistent feature across all agropastoral zones, with the major factor influencing productivity being cattle stocking density (Otte and Chilonda, 2002).

Improved nutrition, management and health within non-traditional systems such as in South Africa (Visser et al., 2020; Oduniyi et al., 2020) that are more aligned with higher performing production systems elsewhere in the world, contribute to far greater on-farm productivity and efficiency. Relatively small quantities of beef are exported from some African countries including South Africa, Botswana and Namibia, although health restrictions limit export market access. Recently, Namibia commenced exporting small quantities of beef to the USA, the first African country to do so (Reuters, 2020).

Brief overview of beef production systems

Beef production systems may be broadly classified as extensive including rangeland and pastoral, agropastoral, mixed farming, and intensive. Extensive beef production systems typically include pasture-based cow-calf and stocker/backgrounding or grow-out systems, and pasture or feedlot finishing. Cattle in pasture-based systems are subject to high levels of environmental variation to which specific genotypes are better suited. Strategic nutritional supplementation may be required within these systems. More intensive systems can maintain more control over nutrition and the environment and are more typically used for dairy veal and beef production and during finishing to assure product quality and specifications.

The characteristics of beef production systems vary widely and are influenced by available resources and by market and supply chain development. Beef enterprise characteristics are also determined by whether beef is a primary focus of the enterprise or a by-product of other uses, including dairy production. Beef production systems that use beef cattle genetics include cow-calf and grow-out systems, may include finishing systems. A large proportion of global beef production is also associated with cull cattle, offspring that are a by-product of dairy production. Europe and the USA produce large quantities of dairy beef and veal for domestic consumption, whereas New Zealand is a major exporter of beef from the dairy industry. Increasingly, dairy industry females are being mated with beef breed sires to enhance the volume and qualities of beef and veal produced and includes the use of sexed semen (Pahmeyer and Britz, 2020; Skelhorn et al., 2020).

Cow-calf systems represent 60–70% of production costs to slaughter (Jenkins and Ferrell, 2002). Pasture-based or foraging systems predominate in major beef producing countries such as USA, Brazil, Argentina, Australia, New Zealand, Canada and Uruguay, in some European countries including France, UK and Ireland, and in sub-Saharan Africa. They include grazing and rangeland production within beef only or mixed livestock and farming systems. Pasture-based backgrounding and finishing systems and feedlot grow-out and finishing systems are used to varying degrees in major beef producing countries, depending on available feed resources, environment, market requirements and costs of production. Strategic nutritional supplementation may include by-products and can overcome deficiencies in the amount and quality of pasture- or forage-based feed for the breeding herd, for offspring prior to finishing, and during pasture finishing to ensure efficient growth and target-market specifications are met.

Efficiency of beef production is affected by numerous factors and can be assessed at various levels including animal biological, enterprise, sector and industry (Cottle and Pitchford, 2014). A major impact on efficiency and profitability of beef production is reproductive rate and reproductive efficiency due to the cow-calf phase of production typically accounting for at least 60% of production costs. Reproductive rate is assessed as percentage of calves weaned relative to cows joined. Reproductive efficiency can be defined as weight of calf weaned per cow joined per year (Holroyd and McGowan, 2014), or the ratio of calf weight at weaning to cow weight. Although not currently measurable within extensive systems but important for efficiency of feed resource utilization and enterprise economics, reproductive efficiency should more correctly be defined as maternal DM intake from first mating exposure to weaning (Bell and Greenwood, 2013).

Maternal productivity and efficiency have been reviewed and discussed in detail within the context of production systems by Walmsley et al. (2018). In temperate systems with improved pasture feed base and improved beef cattle genetics the reproductive rates are typically high and can be 90% or more. Extensive rangeland systems with harsher environments and more marked seasonal effects on pasture availability and quality can result in negative energy balance and reduced fatness of breeding females. Hence, reproductive rates can be substantially lower at 50% or so in harsher, more extensive tropical systems such as in far northern Australia, compared to 80 to 85% target weaning rates considered achievable (Holroyd and McGowan, 2014). Maternal genotype is an important consideration and can interact with nutritional and other environmental factors to affect reproductive efficiency (Bell and Greenwood, 2013).

Within systems for growing cattle after weaning, adequate intake of nutrients from pasture and if necessary, as supplements are important to ensure more rapid growth and increased productivity relative to maintenance and to ensure more rapid turnoff of cattle for slaughter or feedlot. This is especially important in seasonally variable beef production systems such as in northern Australia to avoid the costs including feed resources of having to maintain cattle through an additional dry season before target-market weights are achieved (Bell et al., 2011; Burrow, 2014; Greenwood et al., 2018).

Finishing systems require feed of high energy value, typically $\geq$10 MJ ME/kg DM or more to ensure rapid, efficient growth and specified levels of growth and fattening that may include marbling to meet target-market specifications (Hynd, 2014). Where beef finishing systems are used, they generally include fattening of cattle on higher quality improved pastures, or on high energy concentrate feed in feedlots to better meet market specifications and optimize efficiencies (Hynd, 2014).

A well-developed feedlot sector provides additional options for growing and finishing cattle or even maintaining breeding stock.

This includes options during drought, depending on availability and quality of pasture and cost of concentrate feeds among other economic factors, and to achieve market specifications. The USA has the largest beef feedlot industry, although the proportion of beef from feedlot finishing has been increasing in various countries including Australia, Brazil, Canada and Indonesia.

Small-scale subsistence or commercial cow-calf operations that often use indigenous breeds generally rely on cut and carry of forage, or foraging on pasture, stubble and/or browse. These systems are more typical in Asia, Africa and less developed regions of South and Central America. Smaller-scale commercial production using harvested forages, grains and/or agro-industrial by-products are more typically used in Europe, Japan, South Korea and parts of South America. Moderate-scale, more intensive commercial grazing systems occur within more favourable rainfall environments for pasture growth within the USA, Europe, Australia, New Zealand and South America. These systems may be combined with sheep and other agricultural production such as cropping.

More extensive beef systems include grazing and foraging in rangelands across large land areas including in harsher and more seasonal rainfall environments. These systems for beef production are more typical in western North America, parts of South America, and in northern and inland Australia on properties that can range up to millions of hectares (Burrow, 2014; Drouillard, 2018; Greenwood et al., 2018).

Grazing and foraging systems

Grazing and foraging systems for beef production vary widely depending on environmental, animal, and economic factors and their interactions. They require appropriate soil, plant and grazing animal management to maintain productive, sustainable pasture and rangeland environments (Earl, 2014). Factors contributing to the success of grazing and foraging systems can be complex, particularly where there is substantial environmental variation due to seasonal effects and climatic variation including drought. These factors result in the need for systems that can maintain adequate nutrition during severe pasture deficits relative to livestock needs. Approaches to limiting the impacts of climatic variability include increasing the range of forages to incorporate species with differing growth characteristics across seasons, harvest and storage of excess forage, and use of irrigation where feasible. They also include supplementation with forage and/or concentrates and may include feedlots, although in more environmentally sensitive areas supplementary or intensive feeding may be subject to restrictions.

Various defined grazing and foraging systems are used in beef production and provide options to manage and maintain pasture and cattle productivity. In Australia, which covers widely ranging agroclimatic zones and is subject to frequent drought, grazing systems include continuous, set-stocked, rotational, strip, tactical or strategic, cell or time-controlled, and planned systems, as detailed by Earl (2014). Similarly, in the western rangelands of North America, rest-rotational, deferred rotational, seasonal suitability, best pasture, short duration, season-long, and continuous grazing or foraging systems are practised (Frost and Mosely, 2020). Among these systems in extensive environments, evidence exists that rotational or cell grazing is no more productive and is less profitable than set stocking for beef production (Briske et al., 2008; Hall et al., 2014, 2016; Hawkins, 2017).

Temperate, higher rainfall commercial beef production systems typically have higher stocking rates than tropical systems and use native and more productive improved pasture and forages. Irrigation is less practised for beef than for dairy production due to factors including location and production potential of land, availability of water for irrigation, and economic factors such as differing rates of outputs and hence income from the systems. More marginal productivity land for beef production is often used for breeding herds, whereas growing and/or finishing cattle generally require more productive land suitable for higher yielding improved pastures (Hynd, 2014). This reflects the availability and quality of pasture required to ensure adequate intake of nutrients for different classes of cattle depending on their stage of production and desired level of performance (Table 4 and Figs. 3 and 4).

The favoured genotypes within temperate beef production systems are *Bos taurus* breeds and crosses that include British or larger-framed, leaner European breeds. Increasingly, Wagyu and Wagyu crosses or British breeds and their crosses genetically selected for intramuscular fat content are used for markets requiring more marbled meat (Pitchford, 2014; Greenwood et al., 2019). Tropically adapted cattle and their crosses with temperate *Bos taurus* breeds are also increasingly being used in temperate systems in regions where heat tolerance is becoming more important, and due to their high meat yielding characteristics (Greenwood et al., 2018).

Commercial beef production systems in more tropical-seasonal rainfall and arid regions generally have lower stocking rates on larger properties due to limitations to productivity. These limitations can be geological, climatic and nutritional including lower pasture quality than in temperate grazing systems that restricts cattle growth rates and productivity ('t Mannetje, 1981). Introduction of tropical legumes and management to encourage more tropical legumes within grazing and foraging systems aims to redress issues with feed quality in tropical systems (Bell et al., 2011). Tropical and subtropical production systems favour tropically adapted cattle genotypes and their crosses that have heat tolerance and resistance to disease and parasites such as ticks (Burrow, 2014). Tropical beef production systems have distinct wet and dry seasons with correspondingly higher and lower pasture and forage availability and quality. Hence, strategic nutritional supplementation with forages, concentrates and/or lick blocks is necessary to provide additional energy, protein or nitrogen and minerals to maintain productivity during the dry season (Poppi and McLennan, 2010). This can avoid the costs of having to carry cattle destined for slaughter through additional dry seasons to meet target live weights, although lower cost options particularly for nitrogen or protein supplements would enhance their use (Poppi and McLennan, 2010).

Grazing management

Grazing management affords beef producers options for optimizing the productivity, sustainability and regeneration of pastures (Earl, 2014). More critical management factors that interact with the soil and the plants they support to affect pasture and forage productivity include: i) grazing or foraging interval which affects plant defoliation, recovery and seeding rates; ii) grazing or foraging period which impacts on duration of exposure of plants to animals; iii) residual herbage mass after grazing or foraging which influences regrowth or recovery potential and subsequent biomass availability; and iv) stocking rate or density which impacts on the above factors and also determines animal productivity per head and per unit of land. The productive potential of pastures during annual production cycles is also affected by the mix of warm and cool climate pasture species and their seasonal growth patterns (Allan and Bell, 1996).

Pasture species productivity within swards can be predicted for planning purposes from historical pasture growth data. However, grazing and pasture management is enhanced by actual measurements of availability and growth which are affected by prevailing seasonal conditions, prior management, and animal consumption and selectivity of pasture species. Measurement of pasture and forage availability and quality and pasture utilization across the production landscape are important to improving productivity of grazing and foraging beef enterprises. More details are provided in the section on 'Measurement tools and applications to enhance beef production' below.

Feedlot and other intensive systems

Feedlots are used to fatten or finish cattle and can also help maintain the supply of nutrients to cattle when pasture availability is grossly inadequate to meet the nutritional needs of cattle such as in drought. Feedlot finishing assures the eating quality of beef for domestic markets and the supply of marbled beef for premium markets including the HRI trade and export markets such as Japan and Korea (Greenwood et al., 2018 and 2019).

Cattle entering feedlots undergo induction programmes typically comprising vaccinations for respiratory and clostridial diseases and parasite treatments. They also include gradual adaptation to a feedlot diet using a starter ration with more roughage and less energy than finisher diets (Gaughan and Sullivan, 2014). Feedlot entry live weights in the USA average 364 kg, and in Australia, cattle live weights at feedlot entry typically range from 280 to 400 kg although for production of heavier carcasses 340–450 kg live weight at feedlot entry is preferred. Feedlot diets provide high energy and include grains such as corn, wheat, barley and sorghum, hay or silage for fibre, a protein source such as soybean, cottonseed, sunflower, canola and lupins, and vitamins and minerals. They may include by-products including dried distillers' grains with solubles which can replace more traditional protein sources if cost-effective, and rumen modifiers (Gaughan and Sullivan, 2014; Hynd, 2014; Drouillard, 2018).

Feedlot finishing diets in the USA typically contain about 11 MJ of metabolizable energy (**ME**)/kg DM (derived from Drouillard, 2018) and 6–12% forage (Drouillard, 2018). Typical Australian feedlot finishing diets have a minimum of 10 MJ ME/kg DM and 11–15% CP/kg DM within diets with 75:25 or 80:20 grain to roughage ratios fed at 2.5–3% of live weight (Hynd, 2014; Gaughan and Sullivan, 2014). Feedlot diets in the USA and Australia are reported to often contain protein in excess of nutritional requirements for cattle that have reached the fattening or finishing phase (Pethick et al., 2004; Gaughan and Sullivan, 2014; Drouillard, 2018). This is primarily due the declining need for protein relative to energy in the diet as cattle approach mature lean body mass. During this phase the proportion of live weight gain as fat increases, and the proportion as muscle or protein decreases.

Feedlot diets aim to maximize efficiency as measured by feed efficiency or feed to gain ratios. This is mostly although not always achieved near maximum growth rates depending on factors including intake and the composition of live weight gain. The degree of marbling impacts on eating quality and achievement of market specifications and is also an important objective for feedlot operations. The primary determinant of expression of marbling within a genotype appears to be total energy balance which is a function of energy intake and net energy available for tissue growth during finishing coupled with the duration of the finishing period (Pethick et al., 2004; Hocquette et al., 2010; Park et al., 2018).

Japanese Wagyu (Gotoh et al., 2018) and South Korean Hanwoo (Chung et al., 2018) production systems aim to maximize intramuscular fat development to achieve highly marbled beef. High costs and inefficiencies exist in the current production systems for highly marbled Wagyu (Gotoh et al., 2018) and Hanwoo (Chung et al., 2018) beef. This includes the need to import 90% of the concentrate feed for fattening Wagyu cattle (Gotoh et al., 2018). Wagyu breeds of cattle are fed in group pens a diet high in energy two or three times daily from 11 months of age until slaughter at 28 to 30 months of age, with unrestricted access to water and blocks with minerals, salt, and a diuretic (Gotoh et al., 2018). During the earlier phase from 11 to 18 months of age, the formulated concentrate portion of the ration increases from 37% to 86% with corresponding reductions in roughage which includes beer bran, hay and rice straw. Subsequently, from 18 months of age to slaughter, the ration comprises 86% to 84% concentrate and 14% to 16% roughage. Hanwoo cattle are fed a concentrate with 69% TDN (10.2 MJ ME) and 14% CP per kg DM plus *ad libitum* pasture or rice straw from 6 to 11 months of age. They are then fed a concentrate with 71% TDN (10.5 MJ ME) and 13% CP per kg DM plus *ad libitum* rice straw from 12 to 20 months of age. Finally, they are fed a concentrate with 73% TDN (10.8 MJ ME) and 11% CP per kg DM plus 10% rice straw from 21 to 29 months of age (Chung et al., 2018).

Table 4
Typical minimum herbage mass (kg of green DM per hectare) required to maintain satisfactory production levels in grazing cattle (Bell, 2006).

Class of cattle	Digestibility of pasture 75%	68%	60%
Dry cow	700	1 100	2 600
Pregnant cow (7–8 months pregnant, not lactating)	900	1 700	ns[2]
Lactating cow (with 2-month-old calf)	1 100	2 200	ns
Growing cattle (% of potential growth)[1]			
30 (0.39 kg/d)	600	1 100	2 900
50 (0.61 kg/d)	800	1 600	ns
70 (0.85 kg/d)	1 200	2 600	ns
90 (1.12 kg/d)	2 200	ns	ns

[1] Predicted growth rates in brackets are based on a weaned 13-month-old steer of approximately 320 kg live weight from a cow with a standard reference live weight of 500 kg.
[2] ns = not suitable: at these digestibilities, no matter how much pasture is available, pregnant stock are unable to maintain live weight, lactating stock are likely to experience an unacceptable level of weight loss, and growing stock will not achieve higher targeted weight gains.

Efficiencies of feedlot production and target market dictate the genotypes of cattle preferred for feedlot finishing. Higher yielding cattle that may be bred from high-yielding terminal-sire European breeds are favoured for efficient, leaner beef production using shorter feedlot finishing periods (≤100 days) to improve consistency of eating quality. Higher-value markets that demand highly marbled beef including export markets to Japan and South Korea require longer-feedlotting periods (100 to ≥350 days, including up to 600 days). Growth in these markets has resulted in selection pressure for marbling in British breeds and increased use of Wagyu and Wagyu-cross cattle (Greenwood et al., 2019). Achievement of high levels of marbling also results in high levels of deposition of fat in the other depots and the associated costs and inefficiencies of feed use (Gotoh et al., 2018; Greenwood et al., 2019).

There is a need to uncouple deposition of intramuscular fat from deposition of other fat depots to reduce use of feed resources, carcass wastage and costs (Gotoh et al., 2018; Greenwood et al., 2019). Genetic improvement through use of selection indices has made progress in this regard although meaningful, practical options other than genetics have yet to be established to uncouple deposition rates for intramuscular fat from those for other fat depots (Greenwood et al., 2019). These efforts would be enhanced by reliable identification prior to feedlot and/or prior to long-feeding of individuals with a greater propensity to marble. Progress towards identification of biomarkers for marbling in live cattle has been limited, although recently several oxysterols in blood were identified as being specifically associated with marbling phenotypes (Hudson et al., 2020). The range of factors known to affect intramuscular fat deposition in cattle including genetics, sex, age and live weight at slaughter, environment, nutrition and growth paths has been reviewed by Pethick et al. (2004); Hocquette et al. (2010), Park et al. (2018) and Greenwood et al. (2019).

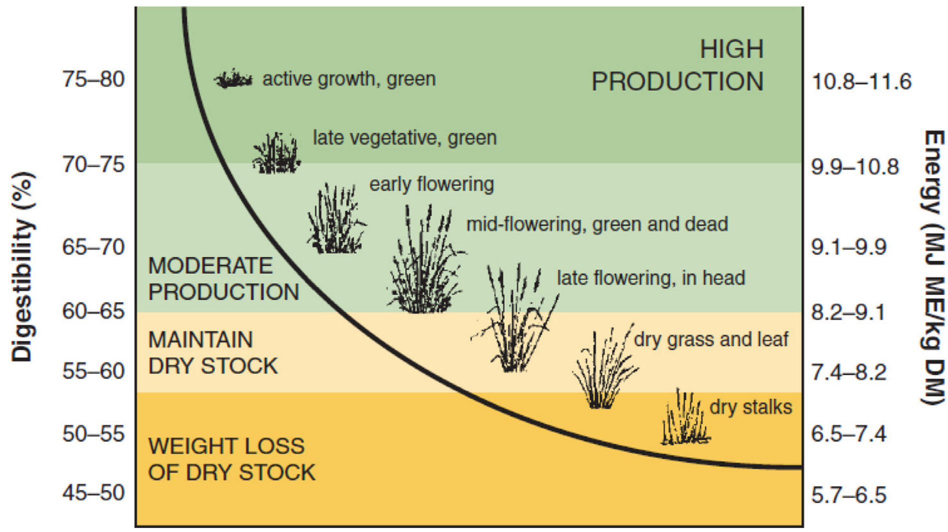

Fig. 3. Phases of pasture growth showing typical changes in digestibility and energy density (megajoules (MJ) of metabolizable energy (ME) per kg DM), with increasing maturity over time for temperate grass species fed to beef cattle (Allan and Bell, 1996).

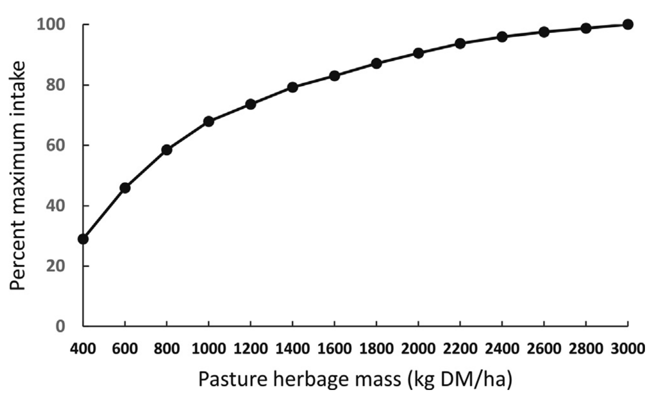

Fig. 4. Typical relationship between herbage mass (kg DM per hectare) and intake of pasture (as percent of maximum pasture intake) for beef cattle (adapted from Bell, 2006).

Consequences of growth paths for beef production

Within grazing systems, particularly extensive systems, the environment results in continual variation in growth trajectories across the different phases of production. These so-called growth paths can have implications for performance during later phases of production including during lot-feeding and on carcass and meat characteristics at slaughter, as described in more detail in reviews by Robinson et al. (2013), Greenwood and Bell (2019) and Greenwood et al. (2019).

Growth capacity during later life can be compromised by conditions adverse to growth during prenatal life which can be compounded by restricted nutrition and growth prior to weaning. Variation in carcass and eating quality characteristics is generally more affected by nutrition and the environment closer to slaughter, i.e., during backgrounding and more particularly during finishing, than by earlier life and developmental programming effects (Table 5; Warner et al., 2010; Greenwood et al., 2019). However, at all stages of postnatal growth additional intake of energy above requirements for lean tissue growth capacity for prolonged periods can result in increased fatness that may persist into later life and may increase marbling (Greenwood et al., 2019). There is also evidence that marbling in offspring may be enhanced by providing grazing mid to late-pregnant cows with supplementary protein (Larson et al., 2009; Underwood et al., 2010; Radunz et al., 2012). While genetic potential for muscling, fatness and marbling establishes capacity for accretion of these tissues, total energy balance as determined by energy intake and the net energy available for tissue growth during finishing is the primary determinant of phenotypic expression of fatness and marbling within a genotype (Pethick et al., 2004; Hocquette et al., 2010).

Evidence suggests few or only modest effects of early-life growth on eating quality characteristics of beef (Greenwood et al., 2019). More immediate preslaughter factors and abattoir processing effects can interact with animal fatness and nutrition prior to transport to the abattoir to affect, for example, muscle glycogen, carcass chilling rates and ultimate pH, which in turn affect meat quality characteristics including tenderness, ageing rates and colour (Warner et al., 2010).

Hormonal growth promotants also play an important role in the beef industries in various countries including the USA and Australia (reviewed by Sillence, 2004; Hunter, 2010). They can markedly increase growth rates, feed efficiency and the proportion of muscle in carcasses and meat. However, they may also have adverse effects on meat eating quality including on beef tenderness and the degree of marbling and can preclude access to certain domestic and some export beef markets such as the European Union.

Measurement tools and applications to enhance beef production

Measurement of pasture availability and quality

A range of methods and tools that measure or predict various pasture characteristics are available or being developed to provide estimates of pasture availability and quality, essentially in real-time as an aid to grazing and pasture management. These can be combined with soil assessments such as moisture content, salinity and fertility to manage soils and manage and predict pasture growth. Currently, the methods most widely used by beef cattle producers to estimate pasture DM on offer are based on visual assessments and pasture height measurement rulers (e.g. Beef + Lamb New Zealand, 2012; MLA, 2020b) or metres that may also have Global Positioning System (GPS) capability (Platemeters, 2020). These methods can be used by beef producers in conjunction with pasture quality testing or with information from visual assessments of the proportion and stage of maturity of plant species within swards. Such visual species-based assessments are based on, for example, the BOTONAL method for estimating yield and composition of pastures (Tothill et al., 1992).

Newer, more automated methods to measure height, DM on offer and quality of pasture are emerging (González et al., 2018). These include existing vehicle-towed and developing robotic pasture height metres with GPS (C-Dax, 2020) and aerial photogrammetry (Viljanen, et al., 2018) for pasture DM measurement and mapping. Ground-based, aerial and satellite (e.g., Satellite Imaging Corporation, 2020) imagery or sensing including across the visible and near infrared spectra to produce vegetation indices and multispectral and hyperspectral data are also evolving. Applications include estimation of pasture ground cover (Meyer et al., 2013), yield (Viljanen et al., 2018) and quality characteristics (Pullanagari et al., 2011; Oliveira et al., 2020). Machine-learning and artificial intelligence are being applied to development of these methods which can be mapped on scales ranging from individual paddocks to the broader landscape.

Measurement of cattle performance

The use and application of various sensor, imaging and other emerging technologies were reviewed in relation to extensive beef production by Greenwood et al. (2014 and 2016), and for livestock production more generally by González et al. (2018) and Halachmi et al. (2019). Technologies exist or are in development for automated measurement of live weight (Charmley et al., 2006; González et al., 2014 and 2018; Simanungkalit et al., 2020), muscling or body composition (McPhee et al., 2017; Miller et al., 2019; Zhao et al., 2020). On-animal sensor devices are also being developed to assess behavioural variables such as time spent grazing or eating, ruminating, walking, lying and drinking, and other cattle performance, health and welfare related parameters (González et al., 2018; Rahman et al., 2018; Halachmi et al., 2019) including intake of pasture (Andriamandroso et al., 2016; Greenwood et al., 2017). Efficiency of cattle in feedlots can also be determined using commercially available equipment to automatically assess feeding behaviours and measure intake of feed and water and live weight of cattle (e.g. Growsafe, 2020; Intergado, 2020). Other fixed and on-animal imaging and sensor devices developed for dairy and extensive beef production systems to assess location, health, welfare and productivity (González et al., 2018; Halachmi et al., 2019) also have potential application in beef feedlots.

Decision support tools and adoption programmes

The application of measurement technologies within beef production systems requires development of tools with interfaces that can be easily used by beef producers and within other enterprises across the beef supply chain (Tedeschi et al., 2021). These decision support tools (DSTs) include genetic improvement programmes and precision management tools to enhance grazing, feedlot, nutritional and landscape management, to optimize reproductive outcomes, and to improve reliability in meeting target-market specifications.

DSTs have been available for many years as herd improvement programmes, such as those offered by breed societies and supported by national and international genetic improvement programmes such as BREEDPLAN in Australia (Pitchford, 2014; ABRI, 2017). Comprehensive beef industry training and adoption programmes such as More Beef from Pastures (MLA, 2020b) will be enhanced as scientific, industry and commercial entities develop new DSTs. The capacity to link objective measurement tools, integrate data across the supply chain, and use of so-called dashboards that enable easy access to a range of DSTs will also support improvements in beef industry productivity and efficiency (Greenwood et al., 2016 and 2018).

Establishment of phenomics platforms for livestock will enhance development of DSTs to improve performance of cattle within their grazing environment and in feedlots. Livestock phenomics platforms can provide a broad and deep array of environmental and cattle performance and physiological data (Greenwood et al., 2016; Visser et al., 2020). In doing so, they will help overcome current limitations to collection of data for development of more relevant productivity and efficiency traits. This is particularly so for traits grazing cattle, to be used in genomic and quantitative genetic selection and in development of management tools and practices (Greenwood et al., 2016). Such data capture and data management platforms will also enable timely generation of environmental and health and welfare metrics to improve cattle well-being and environmental outcomes, which are increasingly being required for provenance of beef sold to consumers (Scollan et al., 2011). New technologies such as virtual fencing can remotely control cattle and herd access to pastures and environmentally sensitive areas without the need for conventional fencing (Campbell et al., 2019 and 2020). Combing virtual fencing with

Table 5
Summary of outcomes for cattle of poor nutrition at pasture and reduced offspring growth during different phases of development, and of pasture compared to feedlot finishing (prepared from results reviewed by Robinson et al. (2013) and Greenwood et al. (2019)).

	Restricted growth during[1]			Pasture vs feedlot
Outcome	Pregnancy	Lactation	Backgrounding	Finishing[2]
Growth to weaning	↓	NA[3]	NA	NA
Backgrounding growth	↓↔	↔↑	NA	NA
Age at feedlot entry	↑	↑	↑	NA
Feedlot/finishing growth	↓↔	↔	↑	NA
Feedlot/finishing efficiency	↔	↔	↑	↓
Slaughter and carcass weights[4]	↓	↓	↓↔	↓[7]
Carcass characteristics[5]	↔	Slightly leaner[6]	Leaner	Leaner
Carcass retail yield[5]	↔	Slightly higher[6]	Higher	Higher
Meat eating quality	↔	↔	↓↔	↓
Marbling	↔	↔	↓↔	↓

[1] Relative to adequate pasture and growth: ↓ = reduced; ↓↔ = reduced or no change; ↔ = no change; ↔↑ = no change or increased; ↑ = increased.
[2] Pasture relative to feedlot at the same growth rate.
[3] NA = not applicable.
[4] At same age.
[5] At same carcass weight.
[6] Unless recovered for a prolonged period on high energy concentrate feed which may result in increased fatness and reduced retail yield.
[7] Carcass weight.

DSTs based on technologies for measuring environment variables, pastures and cattle provides the opportunity to create a step-change in the way cattle are managed. These developments will enhance productivity and efficiency, and the beef industry's capacity to use objective data on productivity and well-being of cattle and environmental outcomes of beef production. Uses of these data will include provision of more reliable, objective information to consumers and policy makers who influence the way in which beef industries can operate.

Conclusions and future perspectives

Increasing population growth and environmental constraints will continue to pressure beef producers and beef industries globally to improve productivity, efficiency and sustainability. Within the more advanced and developing beef industries, these objectives are underpinned by continuing improvements in beef cattle genetics and nutritional and other management practices. These practices will need to enhance reproductive and growth efficiency, carcass and beef quality and animal welfare and environmental outcomes. They should also result in cattle that contribute to improved efficiencies along the entire beef supply chain. More advanced beef industries such as those in the USA and Australia maintain a high degree of flexibility in their options for producing a consistent supply of beef to market specifications. This allows them to deal with continual climatic variation due to longer-term trends, seasonal effects and extreme events such as drought. An array of cattle genotypes and of nutritional options contribute to this adaptive capacity. Nutritional options include grazing, foraging, and strategic nutritional supplementation appropriate for specific classes of cattle and in feedlots including by-product feeds and feeds or feed additives that reduce greenhouse gas production. New measurement technologies will enhance development of decision support tools and adoption programmes for genetic improvement of cattle, and for grazing, nutritional, landscape and supply chain management and contribute to more productive, efficient and sustainable beef industries. The impact of current and future beef industry practices requires on-going, rigorous life cycle analyses to ensure that those practices aimed at improving productivity and efficiencies also have the strategic advantage of better environmental outcomes.

Ethics approval

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Author contributions

Paul Greenwood conceived the content and prepared this manuscript.

Data and model availability statement

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Declaration of interest

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