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Animal board invited review – Beef for future: technologies for a sustainable and profitable beef industry

G. Pulina [a], M. Acciaro [b], A.S. Atzori [a], G. Battacone [a,*], G.M. Crovetto [c], M. Mele [d], G. Pirlo [e], S.P.G. Rassu [a]

[a] Dipartimento di Agraria, University of Sassari, Sassari, Italy
[b] AGRIS Sardegna, Sassari, Italy
[c] Dipartimento di Scienze Agrarie e Ambientali, University of Milan, Milano, Italy
[d] Dipartimento di Scienze Agrarie, Alimentari e Agroambientali, University of Pisa, Pisa, Italy
[e] Research Centre for Animal Production and Aquaculture, Council for Agriculture Research and Economics, Lodi, Italy

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ABSTRACT

The global consumption, notably in developing countries, and production of beef are increasing continuously, and this requires the industry to improve performance and to reduce the environmental impact of the production chain. Since the improvement in efficiency and the highest impacts occur at farm level, it is appropriate to focus on the profitability and environmental sustainability of these enterprises. In many areas of the world, beef production is economically and socially relevant because it accounts for a significant portion of the agricultural production and represents a vital economic activity in mountain and hill districts of many regions, where few alternatives for other agricultural production exist. Due to the important role in the agricultural and food economy worldwide, the future of the beef industry is linked to the reduction of ecological impacts, mainly adopting the agroecological mitigation practices, and the simultaneous improvement of production performances and of product quality. This review analyses the technical and managerial solutions currently available to increase the efficiency of the beef industry and, at the same time, to reduce its environmental impacts in response to the growing concerns and awareness of citizens and consumers.

Implications

Beef supply systems play a significant role in the global agri-food economy. The future of these systems relies heavily on their ability to improve their sustainability in terms of ecological impacts and efficiency. Some technologies are ready to be applied to improve the beef sector at all levels of the production chain. Therefore, technical and scientific knowledge can support the future of the beef supply system responding to increasing citizen and consumer awareness.

Introduction

The world production of cattle meat has increased constantly over the last half-century, with an annual average rate of 1.59%, reaching 67.354 million of tonnes in 2018; the linear, quadratic and cubic temporal trends forecast a further increase in yield ranging from 69 to 89 million tonnes in 2030 (Fig. 1). This trend is part of a continuous global growth in the annual meat availability recorded in the same period, driven by the increase in consumption of all categories of meat worldwide (Fig. 2). However, the specific meat availability dynamic shows that from the first position in the sixties, cattle meat has dropped to the third most consumed since the beginning of this century (8.8 kg/person in 2018); on the other hand, pig meat that dominate individual consumption for fifty years has recently been overtaken by poultry meat (15.8 vs 16.7 kg/person, respectively), which is going to become by far the first most eaten meat in the world. Obviously, this forecast does not consider the short-term impact of the Covid19 pandemic, which, as stated by OECD-FAO 2020-29 outlook (2020), "is uncertain, but meat production (including both slaughtering and processing) and consumption patterns, especially those of food services, are expected to be affected" nor that of the "pig meat output [which] will remain subdued in the first five years of the outlook period due to the ASF outbreaks, in China and Viet Nam in particular".

The relative decline in the availability of beef for human consumption over the other meats, expressed as a ratio of production to world population, shows a pronounced trend over the last four

* Corresponding author.
E-mail address: battacon@uniss.it (G. Battacone).

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decades. This negative trend could be due mainly to the lower productivity of the beef industry compared with that of the other livestock species reared for meat production. In fact, compared to other more prolific species at slaughter, pigs multiply 10–15 times the reproductive live weight (**RLW**, kg of reproductive female and replacement reared), chicken nearly 100 times, while in the case of cattle, this indicator is far below the parity.

By using the data of FAOstat (2020) and assuming on a global scale, an average BW of kg 250 for cattle, kg 70 for pigs and kg 1.72 for chicken and including the biomass of reproducing, raising and fattening animals, the average estimate meat output (kg of carcass produced per kg of BW maintained) for cattle (0.181 kg/kg) is of one order of magnitude lower than that of pigs and chicken (1.765 and 3.188, respectively) (Table 1).

While in no way being able to reach the performances of the other species, the improvement of reproductive and productive efficiency is the prerequisite for an economic and environmentally sustainable beef industry. It is undisputed that the intensification of processes with higher outputs per animal unit maintained is the major driver of the sustainability of animal productions (Pulina et al., 2017) from the environmental impact point of view, as demonstrated for GHC and water-footprint (in extensive literature, Mekonnen et al., 2019) that is not disconnected from economical purposes (Åby et al., 2013).

Among the recent pre-COVID analyses and outlook on the beef industry produced by the Asian-Australasian Journal of Animal Science (Smith et al., 2018), it is worthwhile to considering the European (Hocquette et al., 2018), US (Drouillard, 2018), Chinese (Zi Li et al., 2018) and Australian (Greenwood et al., 2018) ones; an extensive analysis of the strategies to improve the productivity of beef cattle production has been published by Terry et al. (2021).

In many areas of the world, beef production is economically and socially relevant because it accounts for a significant portion of the agricultural production (see Supplementary Material S1). It represents a vital economic activity in mountain and hill districts of many regions, where few alternatives for other agricultural production exist. On the other hand, despite the increasing vulgate that depicts beef production as the lowest protein productive and the highest environmentally damaging among animal derived foods, an increasing amount of literature advocates for metrics that compare meat production efficiency by taking into account the conversion rate of edible human food in animal proteins and presents a new ranking in which cattle meat appears at the higher level of convenience for using these feed resources (Mekonnen et al., 2019; Terry et al., 2021).

Even if the main source of the beef supply comes from specialised cattle breeds, a significant proportion originates from dairy herds, which contribute in terms of finished dairy steers, cull cows, finished heifers and cross-bred calves obtained from dairy cows inseminated with semen from beef cattle (see Supplementary Material S2). In the EU, where two-thirds of cow herds are of the dairy type, the beef market is influenced by the dynamics of dairy cattle (European Commission, 2018).

Since the production of beef plays an important role in the world economy of agriculture and food, its future is linked to the reduction of ecological impacts and the simultaneous improvement of production performances (Scollan et al., 2011). This review analyses the technical and managerial solutions currently available to increase the efficiency of the beef industry and, at the same time, to reduce its environmental impacts in response to the growing concerns and awareness of citizens and consumers. After an analysis of beef supply chain systems, productivity and reproduction identifying critical points and opportunities for the beef supply chain, and feeding and management supported by precision breeding, the paper proposes strategies to reduce the carbon footprint of beef farming and the relationship between feeding and nutrition technologies to reduce environmental impact. The prospects for the beef industry are then illustrated by exploring whether agroecological farming systems and consumer choice can play their role in a sustainable development of the beef supply chain.

Beef chain systems, productivity and reproduction

Beef production contributes to the economy, rural development, social life, culture and gastronomy of most countries and is characterised for diversity of genotypes and animal categories (cow, bull, steer, heifer, veal) and farming systems (intensive, extensive on permanent or temporary pastures, mixed, breeders, breeder-feeders, feeders, milk-fed, specialised or not, combined with other products) (Smith et al., 2018; Ryschawy et al., 2019). Therefore, it is possible to identify different farming systems, varying between and within countries, where the cow-calf system

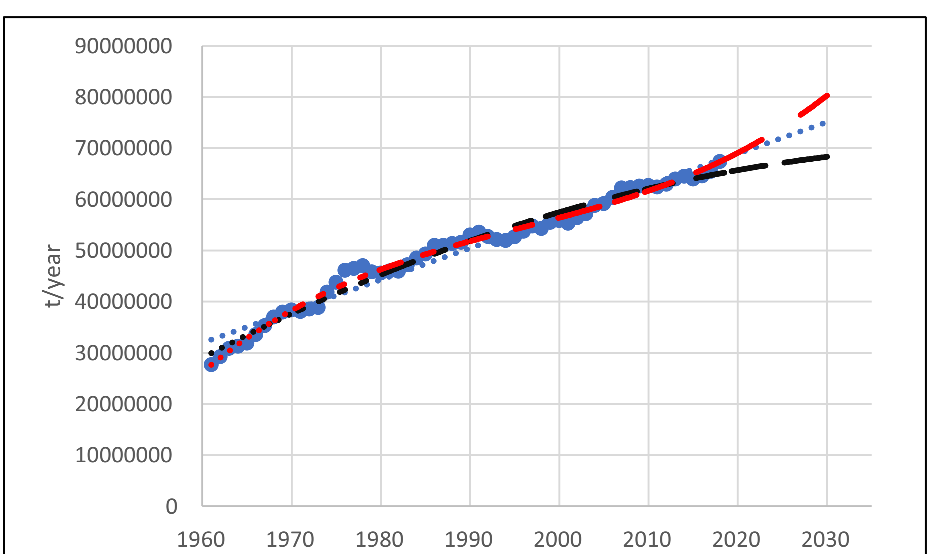

Fig. 1. World cattle meat production: linear (blue), quadratic (black) and cubic (red) time series (elaboration on FAOstat data, 2020).

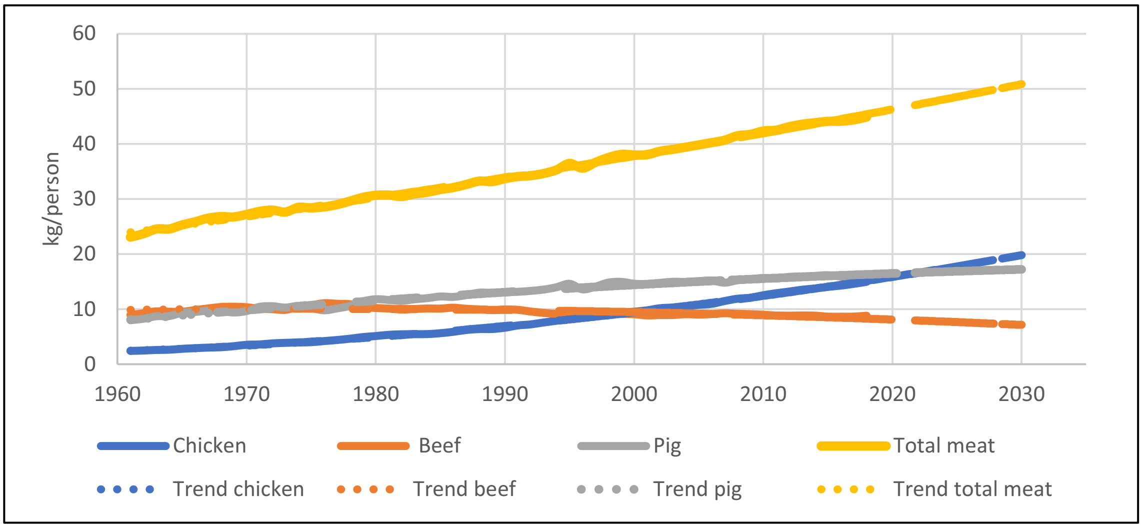

Fig. 2. Apparent individual consumption of beef, chicken, pig and total meat (in kg/person per year): quadratic tie series (elaboration on FAOstat data, 2020).

forms the basis, from those selling weanlings through to finishing heifers, steers or bulls. In regions in the world where cattle breeding is specialised in meat production, a functional way to identify these livestock systems is to divide them into closed and open productive cycles.

In the closed-cycle, meat production takes place on the same farm, where animals are reared mainly on pasture, although concentrate supply and short period of housing during last fattening phase are also possible. This system is widespread in Australia and South America (Rearte and Pordomingo, 2014; Millen et al., 2011). In Europe, the same system, which also includes meat from culled animals, is widespread in north-western countries (such as Ireland, Great Britain and part of France), where animals are slaughtered at greater ages (over 2 years) and live weights, than in other parts of the continent (Mathews and Johnson, 2013).

In the open cycle system – where the beef production is segmented into several ownerships between the time animals are weaned and slaughtered – the weaned calves are the primary product of cow-calf farms, and they are sold to stockers providing backgrounding lots or feedlots. This system of beef supply is widely used in North America (Drouillard, 2018), but it is gaining popularity in South American countries such as Argentina and Brazil (Rearte and Pordomingo, 2014; Millen et al., 2011). In Europe, this segmented system is common in Central-Eastern and Southern Europe. The operations adopted in these systems in different countries are reported in Supplementary Material S3.

Critical points and opportunities for beef supply chain

Although beef production has increased rapidly over the past 50 years using many techniques, the economic analyses showed that the fattening enterprises usually yield low returns. Production input cost and management are frequently cited as important factors affecting profit, but the factors influencing the profitability of cattle fattening enterprises are numerous, diverse and often interconnected (Göncü et al., 2017). However, innovative approaches that provide consumers with more accurate information on the true quality of beef, or even of the different anatomical cut, appear as highly performing to obtain a clear pricing process profitable throughout the beef supply chain (Bonny et al., 2018).

The main limit for the beef industry is the low production output per reproductive live weight maintained (RLW, kg of cow and replacement reared at the reproductive phase), that can achieve parity (one kg of BW sold per kg of RLW), thanks to the contribution of the dairy industry by the over replacement of cross-breed males and culled cows. Limiting the analysis to beef cattle, this indicator is usually lower: in the US cattle industry based on extensive reproduction and intensive fattening it hardly exceeds a RLW value of 0.7 (Mekonnen et al., 2019).

In accordance with Diskin and Kenny (2014 and 2016), to have good reproductive efficiency in beef herds, it is essential to achieve some targets:

- 365 days of calving interval,
- less than 5% cows culled annually as barren,
- more than 95% of cows calving to weaning a calf,
- heifers calving at 24 months of age,
- compact calving with 80% of cows calved in 42 days,
- replacement rate 16–18%,
- sustained genetic improvement of the cow herd for economically important traits relating to reproduction (calving ability, and calf weaning weight),
- close alignment of calving date with onset of pasture availability in the spring.

Table 1
The global output of beef industry compared to pig and chicken industries (elaboration on data FAOstat, 2020).

Species	Head (miles)	Meat (kilotons)	Animal slaughtered (miles)	BW/head (kg)	BW total (kilotons)	Meat/BW (kg/kg)	Head slaughtered/head maintained	Meat for humans use (kg/person)
Cattle**	1 489 744	67 354	302 128	250	372 436	0.181	0.203	8.620
Pig	978 332	120 881	1 484 493	70	68 483	1.765	1.517	15.470
Poultry**	23 212 565	127 298	68 785 221	1.72	39 925	3.188	2.963	16.291

*Human population estimate at September 2020 is 7 814 million of heads (Worldometer, 2020).
** Cattle also produce milk and poultry also produce eggs.

Calving-to-calving interval, heifer calving at 24 months of age and herd fertility, can be considered more important reproductive factors to influence beef production.

Calving-to-calving interval is conditioned by calving-to-conception interval, which depends on resumption of oestrous cycles postcalving; nutrient intake, before and after calving, is a major factor affecting the duration of the postpartum anoestrous interval and overall pregnancy rate. To evaluate the nutritional status of the herd at a given time, point body condition score (**BCS**) is a useful method (easy to apply and practical) for this purpose.

Renquist et al. (2006) observed decreases in calving interval when BCS at calving increased from 3.5 to 4.5 (scale 1–9); at the same time, cows with moderate BCS (4.5 and 5.5) at weaning tended to wean heavier calves than cows with either low or high condition. Moreover, BCS at weaning (about 6 months prior to calving) was related to birth weight, in fact, dams with a BCS at weaning of seven birthed heavier calves than dams with low (3–4) or high (8.5) BCS.

Since replacement represents an important investment for breeders, it is necessary to pay close attention to heifer management in order to get the first calving as soon as possible. Traditionally, the recommended target weights for beef heifers at puberty (prebreeding) were 60–65% and at first breeding 65–70% of estimated mature weight, so as to attain 85% of mature weight at first calving, this condition allows the heifers to minimise dystocia and facilitate postcalving oestrus resumption and successful rebreeding (Diskin and Kenny, 2014).

For better reproductive efficiency of the heifer, it is essential to keep in mind that rate of growth preweaning and early postweaning has a more profound effect on reproductive success in the first breeding season than immediately preceding the breeding season, confirming that weaning weight has a major impact on timing of puberty (Day et al., 2013).

Manipulating the growth of heifers between weaning and their first breeding season with appropriate feeding plans is an effective tool to reach the optimal BW and ensure breeding success. For the latter objective, both the calving result and the ability of the heifer to give a good first lactation are important, since the result is the first calf weaned and ultimately to be able to produce a calf each year. Schubach et al. (2019) carried out a trial with Angus × Hereford heifers, weaned at about 201 d age and fed during the growing phase (182 days) using different diets to maintain a limited, a moderate or an elevated BW gain. The feeding plan affects the onset of puberty that was delayed in heifers with limited BW gain; moreover, the final puberty attainment was greater in heifers with elevated BW gain than in the other two groups.

The economic importance of reducing the unproductive period of heifers is highlighted by López-Paredes et al. (2018): analysing lifetime production of 7 655 cows (a total of 27 118 parity records from 301 purebred Blonde d'Aquitaine), they observed a reduction of heifer feeding cost of €17.7, a reduction of production cost of €22.1, and a profit increase of €21.50 per slaughtered animal per year over lifetime cow production, shortening the age at first calving, from 3 to 2 yrs. Boyer et al. (2020), in a study analysing the reproductive failure impacts on the profitability of raising replacement heifers in the U.S. beef cattle system, showed that the economic result, evaluated in terms of expected net present value, is positive when the heifer/cow does not lose a calf or lose only one calf in their productive career, whereas if it loses two calves, the economic result is negative. The investment cost for the dam is recovered with six calves without losing any; on the other hand, one or two calves lost, requires the production of nine or ten calves, respectively, to recover the investment. These results suggest that when a dam loses a calf, it may not be profitable for the farmer to continue to breed from it; such evaluation clearly reinforces the economic relevance of a good choice of heifers according to their fertility and therefore the length of their reproductive career.

Many management factors can affect fertility in beef cows. The most critical time for embryonic mortality is between days 5 and 42 after insemination, when the embryo passes into the uterus and the implantation of the embryo to the uterus is completed. This period is critical for embryo survival, because of its vulnerability to any changes in the uterine environment due to stress factors (such as shipping and heat stress) or change in nutritional status (acute negative energy balance), all of which modify components of uterine secretions or influence the circulating concentrations of progesterone that regulate the uterine environment (Perry et al., 2011). Other management factors can influence fertility, such as artificial insemination performance (oestrus detection, inseminator efficiency and semen quality) and mating capacity of bulls (libido, semen production and quality, bull/cows ratio). Whatever the reproductive technique (artificial insemination or natural service), the use of hormonal stimulation can increase pregnancy rate and consequently livestock profitability (Baruselli et al., 2018). However, increasing the fecundity (number of calves born yearly per cow) or compacting the life cycle by adopting alternative rearing schemes represent the actual strategies to improve the productivity of beef chains.

The improvement of beef profitability by enhancing twin births in cattle is a technology in field since the 1970s. Normally, in beef cattle, twinning occurs in 1–5% of calving (Moioli et al., 2017), and triplets are rare. The breeders contrasted twins for a long time principally for free-martinism, but also because of the problems related to less foetal survival, retained placenta, dystocia and longer interval parturition to conception.

The most important contribution was provided by the MARC at the Clay Center in Nebraska, where an experiment started in 1981 with the aim of improving the twinning rate by selection. By founding a twinning herd with 307 cows displaying a calving rate of 1.11, the project proceeded for 25 years registering an increase of 3 % $year^{-1}$ on ovulation and calving rate and achieving in 2004 a twinning rate of 1.56; the cows that gave twins produced 52% more BW in calves at weaning that, at farm level means an increase in income of 45% with 50% of cows producing twins (Cummins et al., 2008). In the same experimental prolific herd, Echternchamp et al. (2007) observed that the twins born from cows which ovulate bilaterally displayed higher survival and BW at birth, longer gestation and fewer dystocia problems than those born from unilateral ovulation. These authors reported also higher foetal abortion, shorter gestation length and less survival in triplets than in twins and single parturition. When transferred to commercial situations, the achievement of the prolific experimental herd encountered some non-predictable difficulties: higher death of twins than single (20.2% vs 3.4%, respectively), stronger risk of being open for two-bearing cows, lower twinning rate than expected by the breeding value calculated in the reference herd (Cummins et al., 2008).

In Italian autochthonous Maremmana breed cattle, Moioli et al. (2017), by using genomic kinship matrix estimated through genomic marker data, calculated the twin character genomic heritability of 0.29 ± 0.021, and found that the most significantly detected single nucleotide polymorphisms (Hapmap22923-BTA-129564) were located in proximity of two genes, ARHGAP8 and TMEM200C, which might be potential functional candidates for twinning rate in cattle. Phenotypically, they also found a higher mortality in twins than in single (26.6% vs 5.2%, respectively), but they did not register any difficult calving probably because of the well-known calving ease of the Maremmana breed.

In short terms, even if twin calving represents a mature technical tool to increase beef industry output, the practical problems present at commercial herd level could have limited its diffusion.

However, an accurate analysis of pros and cons tailored for the single farm, which consider local (staff skills, labour cost, availability and cost of veterinary services, housing facilities, etc.) and general (climate, feed costs and meat prices, transportation facilities, etc.) conditions, can widen the application of this technique. An example of increasing output of the prolific scheme applied in a herd under Mediterranean conditions with a twin rate of 50%, calculated by using the mortality and carcass performances measured by Echternchamp et al. (2007), is presented in Fig. 3b compared to a regular herd (Fig. 3a): the twin scheme makes a 21% increase of carcass output possible. An alternative way that could increase the carcass output per cow maintained in the herd is the "manzarda" scheme. Manzarda is the Italian name for a primiparous cow with a precocious calving (26 months) that is slaughtered at 36 months, after a brief fattening period, contemporaneously with its finished offspring. In this case, as illustrated in Fig. 4b, the yield is 18% higher than that of the regular herd (Fig. 4b). Finally, combining the "prolific" and "manzarda" schemes, at the same level of parameters used in Fig. 3a,b, 4a, and considering the twin female born in unisexual calving event useful for reproduction (28% according to Echternchamp et al., 2007), the yield can achieve 43% more than the regular herd (Fig. 4b).

To improve reproductive efficiency (and consequently profitability) in beef farms, in some cases, it is sufficient to spread the application of techniques that have already existed for a long time (such as the synchronisation of oestrus and artificial insemination). These always require an economic evaluation, which varies according to the farm conditions. In some farms, it may be sufficient to programme the breeding season, utilising oestrus synchronisation and natural service, to concentrate calving in the season with greater pasture availability. In other farms, it might be more profitable to resort also to artificial insemination techniques and the use of sexed semen. With a synchronisation programme, all females would have three opportunities to conceive by the end of a 45-day breeding season, given an average oestrous cycle length of 21 days. More than 60 days are required without synchronisation. The advantage of sexed semen is that replacement heifers could be produced from select cows and sires that meet the specifications for the maternal herd; the remainder of the herd could be bred to terminal sires that excel at growth and feed efficiency and meet the necessary carcass requirements (Johnson, 2005). The application of embryo transfer on a large scale appears more difficult due to the numerous factors that can affect the result.

In beef farms involving reproductive plans that provide the embryo transfer, the main concern is the management of the recipient rather than the donor cow, because the former bears the physiological effort of gestation and will support the first rearing phase of the high genetic merit calf. Selection and identification of high-quality recipients are not simple: not only is it necessary to know their history of fertility, but they have to be cycling, have a high plan of nutrition and an adequately sized, normally shaped pelvic canal; in addition, recipients should be less than 8 years old, and be structurally sound. Highest fertility occurs in herds where handling facilities are designed to ensure that cattle are managed with a minimum of stress.

In a recent paper, Thompson et al. (2020) started from the concept that the intensification of supply chain sustainability is based on the maximisation of production per unit of land to recommend the "suitable cow size" as a tool useful for farmers to make informed decisions on their specific environmental conditions. This study carried out by using the data collected for cow herds from 2011 to 2018 in the US Upper Midwest shows that lighter weight cows increase the calf weaning weight per land unit. The conclusion was that critical analysis should be done for every productive condition to provide useful recommendations for producers to make informed decisions in terms of opportunities to maximise their productivity.

Feeding and management as supported by precision livestock farming

Major challenges in beef nutrition are tied to objectives of feed efficiency which are often pursued through improvement of residual feed intake (**RFI**). This parameter is largely used in genetic selection for feed efficiency since RFI deviation assures broad additional genetic variance even if this calculation is phenotypically independent from the performance trait but it does not (also) assure the genetic independence (Kenny et al., 2018). Although this trait has been used for many years, a recent review of Kenny et al. (2018) stated that there is still a lack of scientific knowledge necessary to unravel the biological regulation of the trait, especially on the contribution of appetite control, gastrointestinal function as well as cellular energy and metabolism that might help to optimise body composition and stage of maturity goals also to improve meat quality and reproductive efficiency. In particular also a focus on individual variability is needed (Cantalapiedra-Hijar et al., 2018).

Indeed, nutrition and feeding alone are not enough: it is necessary to link them to animal genetic and management improvements, and to a correct and sustainable use of land. Each territory has its own characteristics and beef farming must adapt to them: extensive systems with pasture are certainly suitable in uplands, whereas intensive systems are preferable in plains/lowlands. Diets in turn must be formulated accordingly, with more fibrous ingredients in extensive systems, and more starchy ones in the intensive systems. High growth performance attained in the intensive fattening systems requires relatively high protein and energy concentrations.

Precision livestock farming (**PLF**) application allows the use of new technologies to automatically monitor any single animal and to take immediate decisions. The PLF has met with great interest in the dairy sector, where reproduction requires special attention. Economic aspects, such as low returns in beef farms, explain the lowest interest of this sector in these technologies. Nevertheless, the use of PLF is slowly spreading in beef farms with applications that can contribute to the improvement of animal management, their productivity and therefore the sustainability of production. Recent studies show the profitability use of sensor data with Machine Learning models to improve both the overall management of beef herds (Barriuso et al., 2018) and specific needs, such as the most critical points of the productive system like the calving-time (Miller et al., 2020). Makinde et al. (2019) confirmed that in Canada, the beef industry is slower to adopt PLF technologies for monitoring individual health and welfare of beef cattle than in other livestock sectors. They speculate that socioeconomic factors could be involved in this disparity because current PLF technologies are not appropriate for beef farmers or their animals, so there is little incentive to adopt them.

There are several sensor technologies that offer more specific alternatives for beef enterprises. Farmers can maximise efficiency using effective monitoring systems in critical periods for ideal targets in order to make optimum profit. For example, environmental sensors that automatically control blinds or window coverings or ventilation help manage barn temperature or humidity.

As feed makes up 50–70% of the production costs in cattle fattening farms, feed efficiency improvement will reduce it in proportion at a whole operation level. Therefore, the monitoring of feed intake during the fattening period is a key factor for profitable production. The use of self-feeders that collect data of intakes enables us to make economic assessments and report the problematic animals (Göncü et al., 2017). Since fresh feed motivates cattle to eat more, automatic feeding or robotic technology systems have a

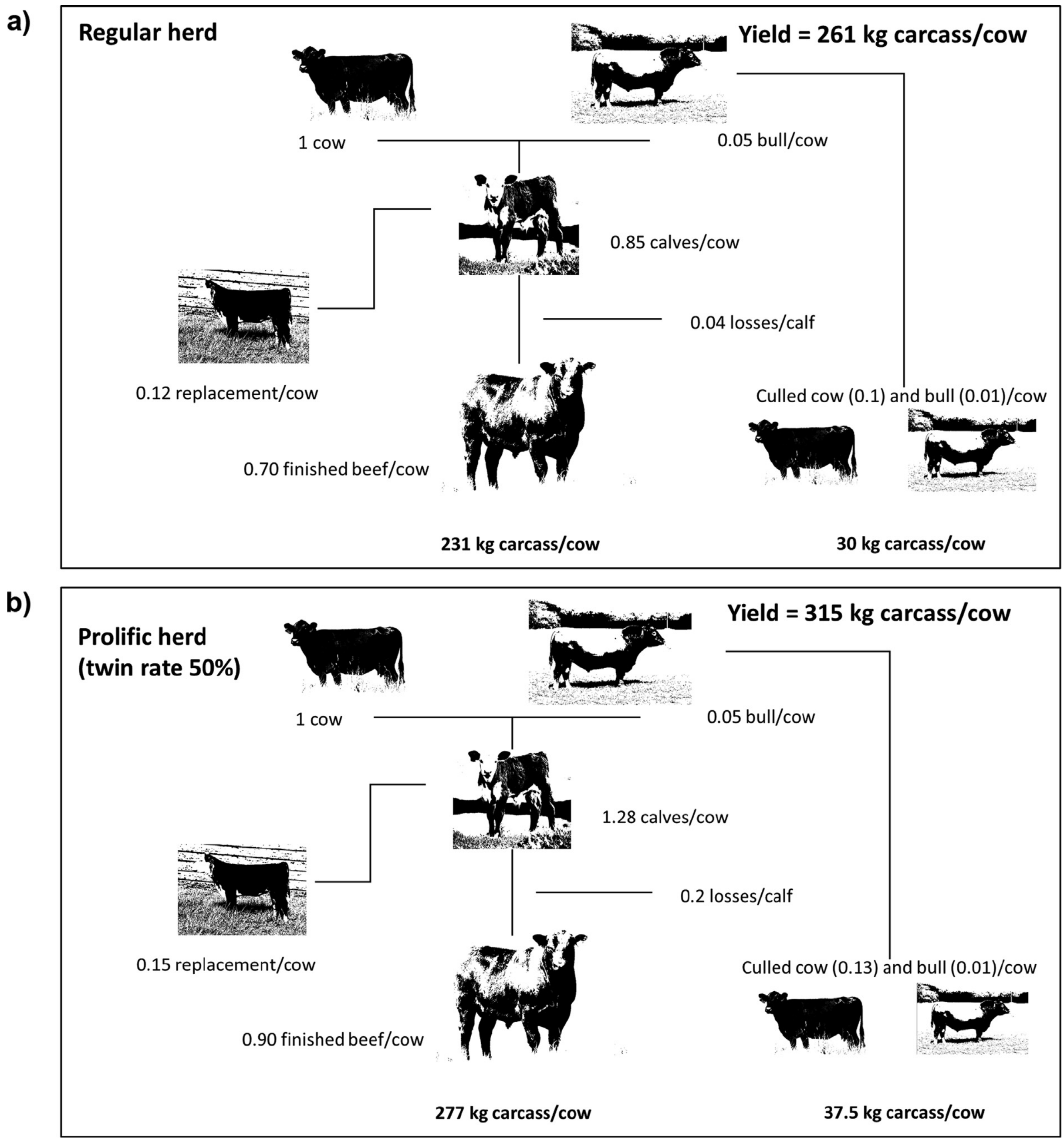

Fig. 3. Diagram of beef system productivity in Mediterranean conditions: flow of regular (a) and prolific (b) herds.

positive influence on fattening profitability, thanks to minimising refusals and labour related to feeding (Makinde et al., 2019).

Automatic identifiers and electronic scales allow farmers to monitor the weight gain at expected dates; at the same time, data collected make it possible to calculate feed conversion rates and help in determining the right marketing time-end of optimum fattening period and to avoid overfeeding (Göncü et al., 2017).

Visual systems automated 3D-acquisition for BCS have been developed, by using different types of cameras that analyse the cow's contours, thanks to the strong correlations between manual and video measures (Alvarez et al., 2018); these devices can be conveniently positioned in association with the automatic weight detector.

Real-time ultrasound – which is an early and convenient non-invasive method to display muscle and fat tissues in live animals – can be used to scan body composition, making it possible to determine maturity and selling price before slaughtering (Pathak et al., 2011).

In extensive conditions, the real-time estimation of herbaceous phytomass (grass) availability by remote sensing from satellite spectral signaland the estimation of animal behaviour (grazing, walking and rumination activity) by means of a collar equipped with a global positioning system (**GPS**) are examples of a precision feeding system which help in management decisions (Oltjen and Gunter, 2015; Greenwood et al., 2017; Bailey et al., 2018).

Differences in activity patterns such as the proportion of time spent grazing, resting, or walking can be quantified and used to compare if, for example, cows were more active when supplement and salt were available. GPS tracking also can be used to quantify the distance animals travel each day and correspondingly be used to help estimate energy expenditure (Brosh et al., 2006). All of these technologies could be enhanced if a true network was cre-

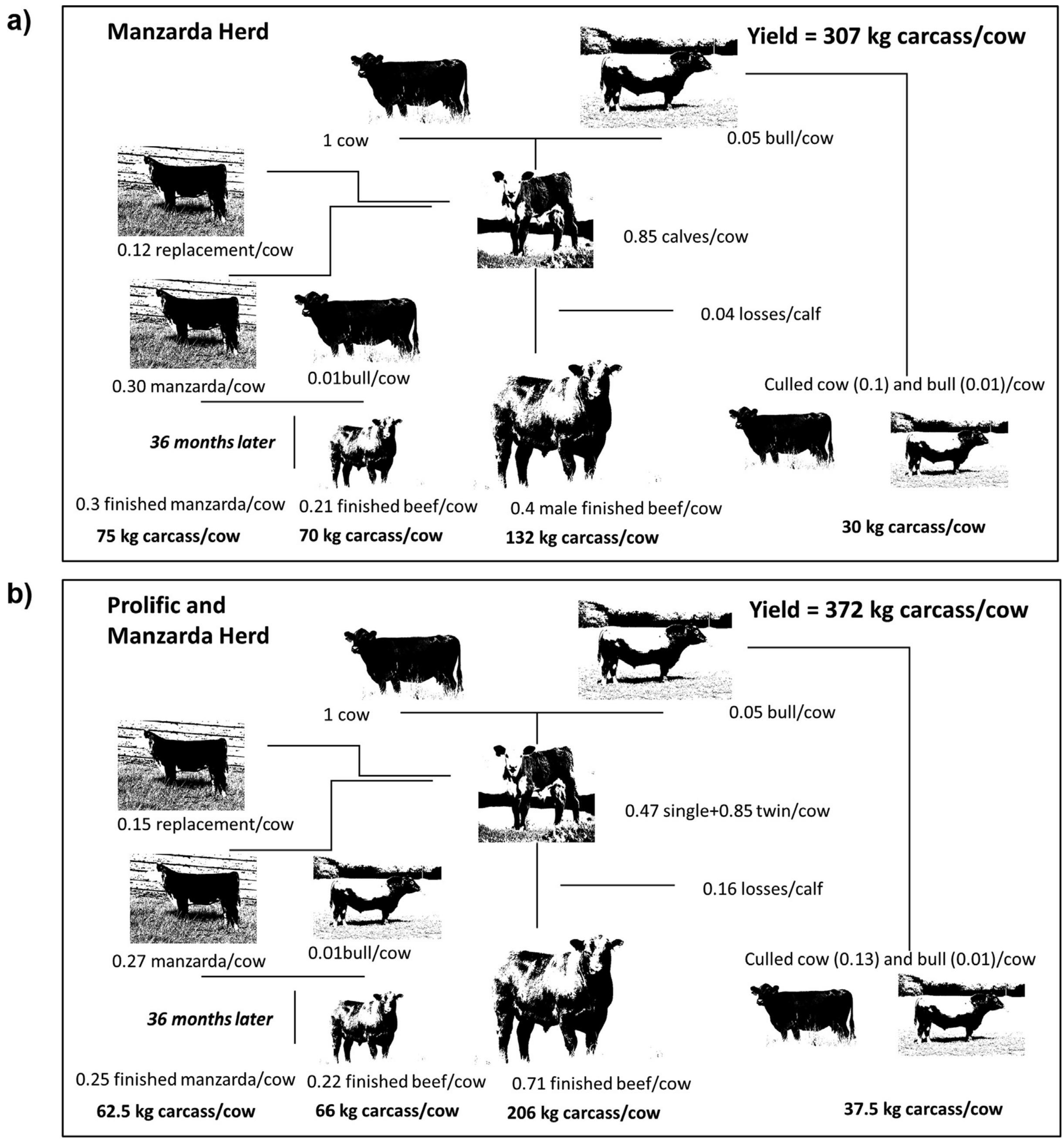

Fig. 4. Diagram of beef system productivity in Mediterranean conditions: flow of "manzarda" scheme herds (a) and flow of "prolific" combined to "manzarda" schemes herds (b).

ated between farmers, extension services, and researchers: the Horizon 2020 SmartCow project (https://www.smartcow.eu/) is one of the best initiatives to bridge the gap between science and agriculture and make the livestock system smarter and more sustainable.

Strategies for reducing carbon footprint in beef farming

Several studies of Life Cycle Assessment (**LCA**) on beef production have demonstrated that the farming system is the main factor influencing the results. However, several criticisms arose for using this approach, mainly due to the allocation problem. In the beef chain, this issue has been recently addressed by Wilfart et al. (2021) who have demonstrated the impossibility of choosing a single "best" assignment rule based only on scientific and technical arguments. "*No allocation rule is perfect, as allocation will always be artificial*". In fact, precise knowledge of the process is indispensable for the correct identification of allocation alternatives. A further shortfall of LCA applied to beef chain is that it does not take into account the effects of land use change, that is the basis of perturbations fluxes of carbon dioxide from and to soil, because it is difficult to estimate them; however, this can cause a lack of information that could lead to mistaken conclusions (Cederberg et al., 2011). Keeping in mind the limits of LCA approaches, Table 2 shows the carbon footprint (**CFP**) of some studies conducted in Italy. Although caution is necessary when comparing results from different studies, it appears that CFP ranges from 26.3 kg CO_2eq/kg of BW, with a local non-specialised breed (Podolica) kept on pasture, to 9.9 kg CO_2eq, with specialised French breeds that are

Table 2
Carbon footprint of 1 kg of BW in different Italian beef production systems.

	System	Carbon footprint (kg of CO_2 kg^{-1} of BW)
Berton et al. (2017)	French–Italian specialised (without carbon sink)	13.0
	French–Italian specialised (with carbon sink)	9.9
Bragaglio et al. (2018)	Local breed in extensive system	26.3
	Specialised breed in extensive	25.4
	French–Italian specialised (without carbon sink)	17.6
	Closed cow–calf intensive	21.9
Buratti et al. (2017)	Conventional	18.2
	Organic	24.6

initially kept on pasture and finished in confinement (this figure is probably too optimistic because it is based on the assumption that grasslands are a perpetual sink for carbon). Table 2 also shows that the CFP associated with the conventional system is lower than that of the organic system. Specialisation has determined an increase in productivity and, consequently, a reduction of the greenhouse gas (**GHG**) emission intensity, i.e., GHG emitted per unit of product. What must be considered when comparing specialised systems with non-specialised systems is that the former are more productive, but are often characterised by higher livestock rates, which could represent a trade-off for water and air quality in some regions, caused by an excess of nutrients that crops and soil cannot absorb.

In a study comparing the environmental impact of conventional (**CON**), natural (**NAT**, similar to CON, but without the use of growth-enhancing technology) and grass-fed beef production systems using models to quantify resource inputs and waste outputs per one million tonnes of carcass weight, Capper (2012) found that the CON system required 56.3% of the animals, 24.8% of the water, 55.3% of the land and 71.4% of the fossil fuel energy more than the grass-fed system. CFP (kg CO_2eq/kg carcass) was lowest in the CON (16.0), intermediate in the NAT (18.8) and highest in the grass-fed system (26.8).

The origin of the calf influences beef CFP: systems based on the insemination of dairy cows with specialised beef breeds have a lower CFP than that of suckler-cows, because the contribution of the mother to the impact is totally allocated to beef production, whereas in the dairy system, the mother's contribution is mainly allocated to milk production (de Vries et al., 2015; van Selm et al., 2021).

In a study comparing four beef production systems, one from suckler herds and three from intensively reared dairy calves, the environmental impacts for the production of 1 kg beef at slaughter in terms of global warming, acidification, eutrophication, land occupation and non-renewable energy use were higher for the beef from suckler herds than for the beef from dairy calves: on average, 27.3 vs 17.9 kg CO_2eq, 210 vs 135 g SO_2eq, 1651 vs 833 g NO_3eq, 42.9 vs 18.6 m^2/year, and 59.2 vs 43.7 MJ (Nguyen et al., 2010).

Similarly, de Vries et al. (2015), reviewing 14 LCA studies, reported that on average lower CFP (−41%), acidification potential (−41%), eutrophication potential (−49%), non-renewable energy use (−23%), and land use (−49%) were attained per unit of beef for dairy-based compared with suckler-based systems. In the latter, maintaining the mother cow is the main factor contributing to all impacts, due to the low reproductive rate of cattle and to the fact that all emissions are allocated to beef production. Comparing the concentrate-based with the roughage-based systems, the authors found lower CFP (−28%), energy use (−13%), and land use (−41%) per unit of beef for the former, while no clear evidence emerged for acidification and eutrophication potential.

Generally, the longer finishing beef cattle are alive, the more environmental impact they have, although the feed used to achieve high rates of gain can in turn have a high impact. Rotz et al. (2019), analysing beef farms in different geographic areas of the United States, noticed that actions to contain the environmental footprint are possible given its wide variation among areas; however, these differences are primarily due to variations in soil and climate conditions that affect the carbon and nitrogen emissions.

Although the North American beef production system, similarly to that of Western Europe, is highly efficient, several mitigation strategies could further reduce the GHG emissions associated with producing beef, with a total reduction of about 20% if multiple strategies are applied to both the cow herd and the feedlot, with the former being by far the most important. Beauchemin et al. (2011) conclude that "when the grassland in the baseline scenario was newly seeded onto previously cropped land, its soil carbon gain more than offset all GHG emissions, changing the beef production system from a net emitter to a net sink of carbon. Although such estimates of soil carbon gain are uncertain, this scenario demonstrates that the net GHG balance of a beef production system is powerfully influenced by carbon dynamics in the associated land base, emphasising the importance of including these dynamics in assessments of mitigation potential."

However, there is also a wide variability in CFP of unit of BW within the same production systems, due to a variety of technical and management practices adopted by beef farmers (Carè et al., 2019).

The variability among production systems and farms demonstrates that there is space for improvements in terms of efficiency, resource consumption and environmental impact. Plenty of researchers have demonstrated that there is a variety of measures, other than nutrition, that can be adopted to reduce GHG emissions from manure, cropping and more in general farm and animal management (see Supplementary Material S4).

The LIFE BEEF CARBON project tested a set of strategies to provide a beef carbon mitigation plan. The project involved more than 2 000 beef farms in France, Ireland, Italy and Spain aiming to reduce beef CFP by 15% in ten years. A list of measures has been proposed to farmers, ranging from animal performance to diet, soil fertility and N-fertilisers, manure management, energy, and carbon sequestration (O'Brien et al., 2020). Some of these strategies were considered to be very effective, such as reduced slaughter age, optimisation of diet CP, anaerobic digestion, preservation or increase of permanent grassland, hedgerows, or trees. Most of the measures suggested can be accumulated to obtain reductions of beef CFP even exceeding the target of the project.

Nutrition and feeding technologies in beef supply to reduce environmental impacts

Nutrition and feeding are fundamental for satisfactory animal performance and they also play an important role in improving production efficiency, lowering costs and enhancing environmental sustainability (Kenny et al., 2018).

The low efficiency of beef cattle compared to swine and poultry is only apparent when the different feed sources are not considered (Wilkinson, 2011). The difference between monogastrics and polygastrics is well known and is primarily due to the digestive system of cattle, which was developed for fibre utilisation. This aspect is highly beneficial as it does not put them in competition with humans, and if we only consider non-edible proteins from humans, beef production could be very efficient, more so than pigs and poultry (Baber et al., 2018). Notwithstanding, feed and energy efficiency are certainly hampered by ruminal processes in the case of diets rich in non-fibrous carbohydrates, so the lower the use of concentrated feeds and the higher the use of forages and by-products, the better cattle will contribute to net nutrient intake for human nutrition (Wilkinson and Lee, 2018).

For ruminants in general and beef cattle in particular, a clear distinction exists between intensive and extensive systems: the latter rely mainly on pasture, while the former strongly depend on cropped fields to supply forages and concentrates. Intensive beef systems generally allow higher levels of production associated with lower environmental impact per unit product (kg daily weight gain, kg carcass, kg meat protein ...).

The high efficiency of the intensive systems is mainly due to the "dilution" of the costs for maintenance: the proportion of energy used for production is greater in animals that are more efficient.

White and Capper (2013) proposed an economic extension of this concept. As reported by White et al. (2015), "when the production system is viewed as a biological entity, development of reproductive females is an energetic and economic cost analogous to maintenance energy at the animal level. Just as the ratio of maintenance energy to growth energy is increased with biological efficiency in an animal, the partitioning of energy from reproductive females to offspring bound for the beef market is improved with higher reproductive rates and reduced calf losses. Managing for improved genetic merit and nutritional management helps to promote the dilution of maintenance at the animal level while improving reproductive efficiency of cattle helps to promote the dilution of maintenance at the farm-system level."

Late age at first calving and relatively limited fertility and prolificacy of cattle are factors which negatively influence beef production and its environmental sustainability. Proper feeding and feed ration balancing are essential for a reduction of the age at first calving and the related environmental costs (Gerber et al., 2015). Precision feeding is, therefore, a tool with animal health and animal management to improve feed conversion and thus spare land for conservation.

Nitrogen and phosphorus excretion

Precision feeding certainly makes it possible to reduce N and P excretion, but nobody has a magic wand, and there is relatively little room for improvement in sustainability.

The importance of giving the required amount of protein and no more to growing/fattening beef to have high growth performance and a lower N excretion has been highlighted by several experiments. Among them, Cole et al. (2005), also referring to other trials, found that the actual CP requirement for optimal performance and maximum N retention was between 11.5 and 13.0% CP on DM for crossbred steers of more than 300 kg LW. Therefore, high dietary protein contents are to be avoided. However, the authors warn that if dietary protein concentrations are decreased to the point that animal performance is adversely affected, then total ammonia emissions could be increased because animals require more days on feed to reach market weight and condition. Because of the decrease in the protein requirements as animals grow and mature, the use of phase feeding should decrease N excretion and ammonia emissions from beef cattle.

Consistently with the last study cited, Vasconcelos et al. (2006) reported that reducing dietary CP during the final stages of the finishing phase of feedlot cattle (e.g. 11.5% on DM) can decrease nitrogen excretion into the environment without reducing animal performance.

A nutritional method to minimise N and P excretion by beef cattle, as with any animal, is to formulate diets that to not exceed requirements for the two elements. Managing cattle diets to meet, but not exceed, metabolic CP requirements is therefore the most practical way to reduce N losses; however, attention must be paid to changes in diets to avoid unintended negative consequences on animal production that would lead to a higher environmental impact per unit of live weight or meat.

In nutrient balance experiments, decreasing dietary P (% on DM) from the actual average 0.35 to NRC-predicted requirements (0.22–0.28) did not influence gain but decreased P input by 33–45% and excretion by 40–50% (Klopfenstein and Erickson, 2002). For nitrogen, the metabolisable protein system may allow more accurate diet formulation, thereby decreasing N excretion. Klopfenstein and Erickson (2002) found that using the NRC model and phasefeeding not to exceed the metabolisable protein requirements over the feeding period decreased N inputs by 10–20% for calves and yearlings without affecting daily gain. Decreasing N inputs led to a concomitant decrease in N excretion (12–21%) and volatilisation (15–33%) in open-dirt feedlot pens.

Diets calibrated on the territory

Globally, the beef chain, which is considered the main producer of meat among ruminants, requires about 2.8 kg of edible human food for every kg of boneless meat (Mottet et al., 2017). However, this system appears to be highly efficient because it converts mainly inedible-human food into high protein concentrated food, becoming, in one of the most important producing countries (the USA), a net producer of human protein (Baber et al., 2018). Actually, maximising meatprotein production per unit of land requires both adapting the livestock system to the territory and using as much as possible of all resources to feed the animals (co-products, marginal areas, food waste, crop residues, etc.) (Van Zanten et al., 2016). Simply put, each cattle supply chain should be adapted to the agroecological condition of its territory.

White et al. (2014) developed a model to optimise the nutritional management of beef cattle to minimise its environmental impact in terms of land use, water use, and GHG emission in the United States. When the model was set for the optimisation of a single-objective, a reduction of 5.4%, 4.3% and 3.6% for land, water use and GHG was obtained, respectively; setting the model for the multi-objective optimisation, an average decrease of the environmental impact of 2.3% was assessed.

In most beef production systems, calves of both genders depend mostly on grazing through weaning (for most around 8–10 months) and later on can continue grazing or being fed total mixed ration in intensive fattening systems where daily weight gains are 2–3 times those achieved on grass (Pierrehumbert and Eshel, 2015). Grass-fed systems invariably produce more methane (CH_4) per unit of beef obtained, because of the greater amount of complex carbohydrates fermented in the rumen and because cattle in such systems take longer to reach slaughter weight. In principle, this disadvantage can be offset by reduced CO_2 and nitrous oxide (N_2O) emission occasioned by reduced on-farm energy usage, reduced use of synthetic fertilisers, and better manure management. However, this offset must not be taken for granted in all grass-fed systems. In their research, Pierrehumbert and Eshel (2015) underline the chief distinction of beef production associated with dairy production, from systems aimed at producing beef alone. The former achieves much lower CO_2 and N_2O emissions than the latter.

Beauchemin et al. (2011) studied how mitigation practices applied to a baseline scenario, described in a previous paper (Beauchemin et al., 2010), can reduce GHG emissions of beef in western Canada where 80% of GHG emissions come from cow-calf and 20% from the feedlot systems. In cow-calf systems, the use of oilseeds in the diet, the improvement of forage quality or the increase of the number of calves weaned resulted in a reduction of GHG, by 8, 5 and 4%, respectively. Applied to feedlot management, feeding strategies appear less effective. However, the increase of forage intake in growing cattle increases the GHG emission by about 6%, whereas each of the other feeding strategies tested, reduced the GHG by less than 2%.

Nutrition and feeding are certainly important for a reduction of the environmental impact of beef cattle. However, only a holistic approach which also includes genetic and reproduction efficiency will offer an effective improvement in terms of environmental impact. White et al. (2015) reported that using expected progeny difference to select bulls, calving window, and optimising nutritional management resulted in a 14.5% reduction in land use, water use, and GHG emissions from the beef production system.

By-products and feed additives

The use of by-products is common and recommended in beef diets, both economically and environmentally (circular economy), but attention must be paid to the level of inclusion in the diets. For example, an excessive amount of total mixed ration in corn or wheat dry distillers grains (10% fat and 30–40% CP, on DM) can decrease methane emission because of the lipid content, but increases N excretion and the probable associated soil N_2O emission, with a resulting 7.8% increase in GHG: 15.2 vs 14.1 kg CO_2 eq/kg LW for beef fed total mixed ration with corn or wheat dry distillers grains in comparison with beef fed total mixed ration with barley grain as main supplemental energy source, standard practice in western Canadian beef cattle diets (Hünerberg et al., 2014). The guideline is always to supply the nutrients (e.g., CP) needed by beef cattle and nothing more. Similarly, manure arising from cattle fed dry distillers grains should be land applied at a level that matches the N requirements of the crop.

Some types of algae, particularly macroalgae (seaweed), contain halogenated compounds (bromoforms and phlorotannins) that inhibit methanogenesis (Kinley et al., 2016), but research is still needed to assure the safety, for human health and environment (ozone depletion), of bromoform-containing algae.

Some feed additives can be considered in beef diet formulation to reduce rumen methanogenesis. Most of them are natural substances (e.g., essential oils, tannins, saponins, etc.) produced by different plants. Fumaric acid has also been tested (Beauchemin and McGinn, 2006), but although it brought about potentially beneficial changes in ruminal fermentation (increased total VFA concentration and propionate proportions, and decreased the acetate:propionate ratio), no measurable reductions in methane emissions were recorded.

Among essential oils, a patented blend of them gave promising results in dairy cows (Belanche et al., 2020). The authors performed a meta-analysis on 23 in vivo studies in which the blend of essential oils was supplemented at 1 g/d per cow; long-term studies (>4 weeks of treatment) revealed that the supplementation of essential oils increased milk yield and feed efficiency without further changes in milk composition and feed intake. Methane production was decreased per day (−8.8%), per DM intake (−12.9%) and per fat and protein corrected milk yield (−9.9%) without changes in rumen fermentation pattern. These results are promising for a possible beneficial use of the additive in beef cattle.

Nitrate, preferably encapsulated, can also be used to reduce methanogenesis in the rumen, being a H acceptor. Lee et al. (2017) found that 2% nitrate on DM decreased CH_4 emission up to 12% in beef cattle. A slight increase in nitrate residues in tissues can be expected following nitrate feeding to beef cattle (Doreau et al., 2018), but at very low levels not considered harmful to humans.

Another interesting feed additive is 3-Nitrooxypropanol, 3-NOP, an inhibitor of the enzyme methyl-coenzyme M reductase that catalyses the final step in methanogenesis. Vyas et al. (2016) reported for 3-NOP (100 or 200 mg/kg DM) an average efficacy of 40% in reducing enteric CH_4 emissions from cattle fed growing and finishing high-forage or high-grain diets, but these effects were negated once 3-NOP supplementation was discontinued. McGinn et al. (2019) speculate that there may be an adaptation to inhibitors over time.

Inputs

Specialised fattening beef farms purchase large amounts of cereals, pulses or by-products, which are often the first source of GHG in LCA studies. For this reason, the choice of feeds influences not only emissions from the digestive tract and manure but also the contribution of purchased feeds to CFP. In general, the use of by-products is beneficial in comparison with the entire feed, because only a part of the environmental burden is allocated to them. For this reason, feeds like beet pulps, bran, sunflower cake or extruded meals are the first choice to reduce contribution of purchased feeds to CFP. This strategy also has beneficial effects on land use or competition between humans and animals.

The origin of feeds also matters, but conclusions from studies are controversial. Sasu-Boakye et al. (2014) found that local protein production contributes to reducing CFPs of pig meat and milk productions, because it requires fewer inputs, such as nitrogen fertilisers. On the contrary, Lehuger et al. (2009) observed that use of imported soybean seems more environmentally sustainable than local-produced rapeseed meal.

Fossil fuels are another relevant input affecting CO_2 emissions and agricultural operations are the main source. Type and number of agricultural operations and equipment influence the farm's energy budget and final beef CFP (Salam et al., 2010). Cropping systems without ploughing and with minimum tillage consume less fuel and are associated with a lower crop CFP.

Utilisation of manure produced on farm is preferable to synthetic fertilisers because this practice reduces Ninputs. However, choice of N-fertilisers can also contribute to reducing beef CFP. This kind of fertilisers requires energy, mostly from non-renewable sources. Although synthesis of urea requires more energy than ammonium nitrate, calcium ammonium nitrate, and ammonium sulphate (Skowrońska and Filipek, 2014), its CFP is the lowest due to its limited N_2O emissions after application (Schils et al., 2013).

Agroecological farming systems for beef production: back to the future

From an environmental point of view, the cow-calf system is associated with higher GHG emissions per unit of beef produced; however, positive ecosystem services are reported due to the contribution of this farming system to landscape shaping, natural biodiversity conservation and the maintenance of the socio-cultural heritage maintaining (Obubuafo et al., 2008; Wiltshire et al., 2011; Alliance Environment, 2020). Moreover, the cow-calf farming system is better perceived by the consumers in terms of animal welfare (Risius and Hamm, 2017). Grain-fed fattening systems are usually more efficient as regards the GHG emission intensity (kg of CO_2 emission per kg of beef), but some environmental clues are reported due to the management of manure, the high density of animals per hectares, the high consumption of grains in competition with food. Hence, the beef chain needs to be improved for efficiency in the first part and for ecosystem services in the second part.

Among these services, carbon sequestration is the most prominent one, but it is matter of intense debate. In fact, the ability to sequester the atmospheric CO_2 is not permanent and the time this ability lasts depends on many factors, such as soil, climate, forage systems, irrigation and fertilisation (Arrouays et al., 2002). FAO (2019) reviewed a list of models quantifying the exchanges of C between atmosphere and soil.

In LCA, carbon sequestration is considered when there is a land use change (e.g., from cropland to grassland) or a significant land management change (e.g., shifting from mineral fertilisation to organic fertilisation). However, so far there is no consensus about the extent of the effects on climate change. There are, at least, two main matters of discussion: i. characterisation factor of CO_2 sequestered, because it cannot be equal to that emitted, but must be related to the length of land use change (how long does permanent grassland last?); ii. how long does land use change or land management change determine a CO_2 removal from the atmosphere higher than the CO_2 emission?

In livestock systems, carbon stock in soil or trees can be improved in different ways. The main rule is to avoid soil disturbance. In the case of mixed systems, there are at least four strategies to increase carbon stocks.

1. Manure addition and cover crops. Continuous application of soil organic matter to a maize-based forage system increases carbon soil stock compared to synthetic nitrogen fertiliser application. Zavattaro et al. (2017), after examining 80 European long-term field experiments, concluded that application of either solid or liquid manure has a slightly negative effect on crop production, but it increases soil organic carbon significantly. Cover crops are effective in increasing the organic carbon concentration in the soil and their capacity to sequester carbon lasts for a long time, without any negative effect on production (Poeplau and Don, 2015).

Reducing agricultural operations. Besides reducing diesel consumption, no or minimum tillage favours C and N accumulation in the soil (Küstermann et al., 2013).

3. Converting croplands into permanent grasslands is considered a strategic measure to increase carbon stock in the soil avoiding the competition between livestock and agriculture to provide direct foods for human beings, especially in those regions where livestock systems are intensive. Castelli et al. (2017) observed a linear increase of C stock for a period of 30 years after the conversion of continuous monoculture of maize to no-till permanent meadow. Arrouays et al. (2002) suggested a net flux of C into soil of about 500 kg/ha per year with a variability of 250 kg of C/ha per year for a period of 20 years, after which there is no significant sequestration. It should also consider that removal of permanent grassland determines a rapid emission of CO_2 to the atmosphere. Temporary grasslands are also sunk into atmospheric CO_2, but the amount of C sequester in the soil depends on the length of the grassland and it is extinguished after ploughing (Dollé et al., 2013). The same authors have indicated a gain of 80 kg of C/ha per year and a loss of 160 kg of C/ha per year as a consequence of the conversion of permanent grassland to cropland (Dollé et al., 2013).

4. Agroforestry. The presence of woods or hedges is a very effective measure to increase carbon stock both in soil and trees. The afforestation of arable land has the potential to increase the carbon stock of 450 ± 250 kg of C/ha per year over 20 years (Arrouays et al., 2002). Creation of hedges also has the potential to increase carbon sequestration, that according to Arrouays et al. (2002) accounts for about 100 kg of C/ha per year. Moreover, according to Dumont et al. (2018) who argued that the convergence between agroecology and sustainable intensification might be a feasible response to obtain socially fair and economically viable ruminant farming systems,agroforestry may be considered a potential candidate to obtain a cross point between sustainable intensification and agroecology.

Agroforestry systems combine crop, livestock, and forest production integrated in the same area and with the efficient use of inputs. The potential of agroforestry to contribute to sustainable development and to future food security has been recognised by the United Nations Framework Convention on Climate Change and by the Convention on Biological Diversity (FAO, 2013). Agroforestry systems are also beneficial to provide ecosystem services such as carbon accumulation, recharge of aquifers, and biodiversity. Moreover, agroforestry systems are more resilient to climate change, providing thermal comfort to the animals.

The ecosystem services provided by the agroforestry systems have been mainly demonstrated in tropical and sub-tropical areas where the need to improve beef production efficiency is highly related to the management of rangeland areas (De Souza Filho et al., 2019). De Oliveira Silva et al. (2016) demonstrated that decoupling beef production from deforestation and restoring degraded pastures are key elements to set up a beef production system for sub-tropical areas able to increase world beef production, without increasing GHG emission. Similar results have been obtained by applying agroforestry systems to beef production, combining the effect of increasing efficiency of beef cattle (due to the improvement of pasture quality) and of the increasing carbon sequestration by pasture and trees. Moreover, microclimate changes associated with agroforestry systems can improve animal performance if compared with traditional grazing systems. According to Giro et al. (2019), in fact, beef cattle maintained in agroforestry systems showed a significant preferential use of shade and a reduction in water consumption. This led to better productive performance and a better use of the natural resources.

Recently, also in temperate areas, agroforestry systems have been considered a feasible opportunity to improve the sustainability and the adaptation to climate change of agricultural and livestock systems (Aguilera et al., 2020). According to the estimation produced by the AGFORWARD project (www.agforward.eu), in Europe, nearly 9% of the utilised agricultural land is currently managed as an agroforestry system, mainly as traditional land use (den Herder et al. 2017). However, the interest in agroforestry also as an innovative production system towards an agroecological transition is increasing (Aguilera et al., 2020). The Italian contribution to the agroforestry system is significant, being the fourth largest area of agroforestry in Europe (1.4 million ha; Paris et al., 2019). Currently, the number of studies on the application of agroforestry systems in beef production in Europe is still scarce. Recently, the CFP of Dehesa agroforestry system for beef production in Spain was reported. The study clearly highlighted that the LCA methodology should also include the carbon sequestration operated by grassland and trees, in order to correctly consider the CFP in agroforestry systems (Eldesouky et al., 2018). Applying this approach to the LCA, the CFP of beef production in the Dehesa agroforestry systems was reduced by 20–30% as compared to the baseline figures, as a consequence of the contribution of carbon sequestration by grassland and trees (Eldesouky et al., 2018). Comparing the GHG emission of the first part of the beef production cycle (suckler to weaning period) with the second part (weaning to fattening in feedlot), the higher values of CFP (expressed as kg of CO_2 per kg of live weight) were usually associated to the first part, due to the higher emission from enteric fermentation (O'Brien et al., 2020). However, considering the role of carbon sequestration played by grazeland and trees in the agroforestry systems, when the functional unit of the CFP analysis is the hectare, the impact of the extensive part of the beef production cycle may be lower than that of the intensive one (Eldesouky et al., 2018).

Consumer's role on the beef supply chain

Every breeding system adopted in beef supply is the result of interactions between multiple factors such as: natural farming conditions, production system (intensive or extensive; conventional or organic), market requirements (fat or lean meat), breed reared and tradition.

Unfortunately, the segmentation of the beef production/marketing chain into a series of sectors (i.e., cow/calf producers, stockers/backgrounders, feeders, packers, retailers, and restaurateurs), which are not integrated among themselves, leads to inconsistencies and quality shortfalls in cattle and beef products, and impedes efforts to align production goals with consumer expectations (Tatum et al., 2000). However, two factors, not strictly classifiable as production factors, are identified as being of particular importance in influencing agricultural systems in future: Community policies and consumer choices.

The Community policies, in particular in Europe, encouraging the extensive system with monetary premiums, make it economically more convenient (higher gross margin per animal and per hectare) than the conventional one, however, the latter produces higher slaughter yield, better carcass conformation, better meat colour and three times higher carcass production per hectare (Keane and Allen, 1998).

The growing requirements of consumers – especially those who have more knowledge on the nutritional and health characteristics of meat – concerning beef production obtained with systems more respectful of animal welfare and the environment, thanks also to the consumer's willingness to pay more, will have a stronger influence on the choices of farmers (Xue et al., 2010; Hocquette et al., 2014).

The consumer is sometimes in contradiction due to lack of knowledge; in fact, it is clear that quality characteristics of grass-fed beef are different from conventional beef (finished in feedlots on concentrate-only diets) in terms of marbling, colour, meat texture, tenderness, juiciness, and flavour. For example, meat from pasture-fed has darker longissimus colour and yellower fat; therefore, it has lower fat thickness than animals finished on concentrate. Although meat colour is not an important characteristic for consumption, it is a major factor in the consumer's choice, bright, cherry-red meat is preferred, while pale or dark meat is less acceptable (Xue et al., 2010). Morales et al. (2013) showed that consumers are not always able to differentiate beef from pasture-fed animals versus beef from farmed cattle based on sensory characteristics alone. In contrast, consumers who are informed about farming systems have favourable attitudes and high acceptability for beef from pasture-fed animals. This difference in consumer preferences for beef quality based on knowledge of origin is well represented by the distinction between intrinsic and extrinsic quality traits, as proposed by Grunert et al. (2004). The high relevance of extrinsic quality traits (such as origin information) on the orientation of consumer choice can be exploited for the development of beef marketing strategies.

The consumer's beliefs in terms of environmental impact led him to an adversity to conventional (intensive) systems of beef production based on limited knowledge that – thanks to genetic improvement, better feeding and management techniques – the environmental impact of the conventional system has been reduced significantly.

The growing attention of consumers for the "reliable eating-quality" of beef inspired some initiatives carried out in different parts of the world (Ardeshiri and Rose 2018; Ellies-Oury et al., 2019) to provide clear and robust indications on the quality characteristics of meat at the moment of purchase/consumption, also replacing the previous ones (Liu et al., 2020). In fact, grading systems differ widely among countries, being some completer than others (Polkinghorne and Thompson, 2010). In particular, the European carcass classification system (SEUROP) proved to be unreliable in reflecting the beef final quality for consumers, because they are not able to perceive differences in cuts obtained from carcasses that belonged to different grading (Bonny et al., 2018).

To overcome these issues, the UNECE has launched an initiative to standardise beef carcass classification based on the system already successfully developed in Australia, which set up the "Meat Standards Australia" grading scheme (Hocquette et al., 2020).

Unfortunately, the meat industry is very conservative and reluctant to any change (Troy and Kerry, 2010), but the upheaval generated by the Covid-S ars pandemic combined with concerns generated by the ideological approach to the impact of beef production systems and competition from fake-meat will force beef chains to adapt quickly to consumer demands.

Conclusions

The profitability and sustainability of the beef industry on a global scale is a matter of complexity. In fact, the variety of breeding systems existing in the world and the number of factors that condition them do not enable us to define a better one; on the contrary, it is necessary to identify the best management strategies in the different breeding conditions, some of which can hardly be changed (e.g., natural conditions). At the same time, it is necessary to think of a constantly evolving production system, associated with the social and cultural development not only of the breeders, who are quite different in the world, but of all the components of the supply chain including consumers. Dairy farming should be considered a relevant source for beef production and optimisation of crossbred procedures indeed more crossbred calves may be produced thus increasing meat production and supply. Opportunities from sexed semen should boost genetic improvement of dairy herds and meat yield quality from crossbred beef × dairy. Beef × dairy also have a reduced environmental impact compared to purebred beef. To reach these goals, the sector clearly needs a focused planning of reproduction in dairy herds, a substantial improvement of meat evaluation systems for high-quality crossbred carcasses and cuts and clear communication to consumers to avoid commercial losses due to crossbred meat promotion, as effectively needed in general for the whole beef chain.

The environmental impact and benefits of beef meat vary significantly among production systems. Experience and literature show that productivity reduces it, whereas there are a lot of strategies other than in nutrition that positively influence environmental performances of beef farms. It will still be necessary to make the beef production sector more economically efficient, more transparent and more reliable to better manage product quality and therefore to improve consumers' trust.

The nutritional/feeding practices that were found to be the most effective in mitigating the environmental impact of beef production are as follows:

- precision feeding: diets formulated to meet animal requirements without nutrient supply surplus (N, P, etc.);
- adequate feeding of the cow herd to optimise the reproduction parameters, reducing the time needed to fatten offspring;
- formulate diets for high performance of beef cattle, particularly in the intensive systems; in this way, the economic and environmental cost of maintenance is amortised on a higher weight gain, reducing the impact per kg carcass or meat;
- improve forage quality to reduce the purchase of external feeds and the concomitant environmental costs;
- use by-products to reduce feed costs and foster a circular economy;
- use some permitted additives to reduce rumen methane emission.

Respect for the environment and animal welfare as well as the quality and health safety of beef will be the cornerstones that will guide the modern development of this sector, thanks to scientific knowledge, the development of precision livestock farming and information technology. Moreover, the convergence of agroecology and sustainable intensification could be a feasible answer to achieve socially equitable and economically viable ruminant breeding systems. Agroforestry can be considered a potential candidate for achieving a crossroads between sustainable intensification and agroecology. However, to attract new generations of breeders, certainly more inclined to use new technologies, it will still be necessary to make the beef production sector more economically efficient.

Ethics approval

None.

Data and model availability statement

None.

Author ORCIDs

Giuseppe Pulina: https://orcid.org/0000-0001-5579-0677
Marco Acciaro: https://orcid.org/0000-0001-7805-9713
Alberto Stanislao Atzori: https://orcid.org/0000-0001-5083-241X
Gianni Battacone: https://orcid.org/0000-0003-2146-6937
Crovetto Gianni Matteo: https://orcid.org/0000-0003-1156-2087
Marcello Mele: https://orcid.org/0000-0002-7896-012X
Giacomo Pirlo: https://orcid.org/0000-0001-9902-2776
Salvatore Pier Giacomo Rassu: https://orcid.org/0000-0001-5669-0993

Author contributions

The authors contributed equal parts to the work.

Declaration of interest

The authors declare that they have no competing interests.

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Appendix A. Supplementary material

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