Specialising and intensifying cattle production for better efficiency and less global warming: contrasting results for milk and meat co-production at different scales

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A B S T R A C T

Cattle are the world's largest consumers of plant biomass. Digestion of this biomass by ruminants generates high methane emissions that affect global warming. In the last decades, the specialisation of cattle breeds and livestock systems towards either milk or meat has increased the milk production of dairy cows and the carcass weight of slaughtered cattle. At the animal level and farm level, improved animal performance decreases feed use and greenhouse gas emissions per kg of milk or carcass weight, mainly through a dilution of maintenance requirements per unit of product. However, increasing milk production per dairy cow reduces meat production from the dairy sector, as there are fewer dairy cows. More beef cows are then required if one wants to maintain the same meat production level at country scale. Meat produced from the dairy herd has a better feed efficiency (less feed required per kg of carcass weight) and emits less methane than the meat produced by the cow-calf systems, because the intake of lactating cows is largely for milk production and marginally for meat, whereas the intake of beef cows is entirely for meat. Consequently, the benefits of breed specialisation assessed at the animal level and farm level may not hold when milk and meat productions are considered together. Any change in the milk-to-meat production ratio at the country level affects the numbers of beef cows required to produce meat. At the world scale, a broad diversity in feed efficiencies of cattle products is observed. Where both productions of milk per dairy cow and meat per head of cattle are low, the relationship between milk and meat efficiencies is positive. Improved management practices (feed, reproduction, health) increase the feed efficiency of both products. Where milk and meat productivities are high, a trade-off between feed efficiencies of milk and meat can be observed in relation to the share of meat produced in either the dairy sector or the beef sector. As a result, in developing countries, increasing productivities of both dairy and beef cattle herds will increase milk and meat efficiencies, reduce land use and decrease methane emissions. In other regions of the world, increasing meat production from young animals produced by dairy cows is probably a better option to reduce feed use for an unchanged milk-to-meat production ratio.

Implications

Many studies advocate selecting high-producing dairy and beef cattle to improve feed efficiency and reduce greenhouse gas emissions. To validate these impacts at the country and world scale, the systemic aspects of upscaling must be considered, notably that the dairy herd jointly produces milk and meat. In developing countries, improving productivities of both dairy and beef cattle seems a valuable strategy to reduce both feed use and greenhouse gas emissions from production. In contrast, in regions where herds are strongly specialised with high milk and beef productivities, it seems preferable to increase the share of meat from the dairy herd.

Introduction

Domestic ruminants are the planet's largest consumers of plant resources, ingesting some 4.85 billion tonnes of DM annually, of which cattle and buffaloes account for 4.32 billion tonnes (Mottet et al., 2017). The capacity of ruminants to digest fibre,

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the main component of plants, through ruminal fermentation, and the diversity of ruminant species enable them to feed on practically all types of plants throughout the world (Jarrige et al., 1995). Human societies have accordingly made extensive use of ruminants as plant biomass processors to convert digestible carbohydrates, especially fibres, into milk and meat, two types of foods of high nutritional value. Ruminants supply other products such as hides and wool, which are, however, being increasingly replaced by cotton and synthetics. They also provide organic fertilisers that remain essential in regions with low access to chemical fertilisers. Finally, large ruminants continue to provide traction power in many parts of the world where they are also used as a financial instrument when economic conditions are unfavourable (Randolph et al., 2007). Hence, an approach restricted to milk and meat productions only can underestimate the potential benefits accruing from other products or services.

Animal husbandry can be a source of environmental and climatic disservices (Steinfeld et al., 2006; Herrero et al., 2015). In particular, livestock farming is increasingly blamed for climatic damage because it emits two powerful greenhouse gases (**GHGs**), namely methane from the enteric fermentation of ruminants and anaerobic fermentation of manure, and nitrous oxide from the management of animal manure for all species. Important nitrogen losses (ammonia and nitrates) contribute to acidification and eutrophication. Furthermore, as livestock activities require more land than crops to provide the same amount of energy or protein (de Vries and de Boer, 2010), world increases in demand for animal products that translate into world increases in supply are the main driver of agricultural land expansion to the detriment of forests and related carbon sinks (Stehfest et al., 2019). There is growing evidence that it will be difficult to feed the world sustainably, and notably to reduce the climatic footprint of the world food system, without changing eating patterns and food diet composition (Willett et al., 2019; Mora et al., 2020). The main changes proposed are "reducing the consumption of animal products where it can be considered excessive, and limiting the growth of this consumption at the global level by curbing the generalisation of the so-called westernisation of food diets" (Guyomard et al., 2021).

Inventory estimates of enteric methane emissions are most often calculated based on DM intake (IPCC, 2006), because of the close correlation between methane emissions and feed efficiencies of cattle (Mogensen et al., 2015). In this review, the feed conversion ratio (**FCR**, expressed in kg of DM intake per kg of animal product) is used to characterise feed efficiency. Improving the latter by increasing milk and meat productivities of dairy cows and beef cattle (Gerber et al., 2011) is expected to be a valuable strategy for reducing not only enteric methane emissions but also the global ecological footprint of ruminant livestock, by saving natural resources (land and water) and emitting less environment-harming waste. In particular, much research advocates increasing milk production per dairy cow will reduce GHG emissions (Monteny et al., 2006; Steinfeld and Wassenaar, 2007; Smith et al., 2008). However, assessing feed efficiencies is not straightforward because of the diversity of resources used, livestock breeds and systems, and the co-production of milk and meat.

Ruminants have the unique ability to convert cellulose into milk and meat. They can thus exploit grasslands, much of which cannot be cultivable and thus are not in direct competition with food. At the world level, 86% of protein used by livestock is not edible as human food (Mottet et al., 2017). However, some grasslands can be used for cultivating crops, and ruminants, notably dairy cows, consume concentrate feed. Furthermore, improving animal productivity requires an increasing use of high quality feed products that are also suitable for human consumption. This implies that any strategy of cattle intensification and specialisation placed in the broader perspective of feeding the planet sustainably should also take into account the complex issue of feed-food competition that is not explicitly considered in this paper. This issue is the subject of an increasing number of report and articles (Mottet et al., 2017; van Hal et al., 2019; Herrero et al., 2021) that however do not address the question in terms of cattle milk and meat specialisation but in terms of substitution between plant and animal products and intensification versus de-intensification of agricultural practices and systems.

All cattle females produce both milk for rearing calves and meat when slaughtered. For several millennia, human societies have known that they can easily milk cows and use part of the milk production to feed young children without adversely affecting the survival and growth of calves. Over the centuries, farmers have thus selected female ruminants that can produce much more milk than suckling animals need and that give milk in the absence of young, making milking much easier (Jarrige, 1979) and contributing to shape the structure of current dairy farming. Besides the orientation of the production system through the choice of a type of breed (dairy, beef, dual-purpose), genetic selection within a breed has aimed at increasing the milk potential of cows or the live weight of beef cattle. This has contributed to the specialisation of cattle, towards producing either more milk or more meat. The specialisation of breeds has been accompanied by an intensification of livestock practices, with important increases in milk yield per dairy cow and in carcass weight gain per slaughtered animal, which has led to the specialisation of herds and has overlooked the fact that animals from dairy breeds also produce meat.

This review paper examines the expected benefits of increased productivity and specialisation of dairy and beef cattle by upscaling literature findings from the animal level and farm level to the country and world scale. It analyses how the co-production of milk and meat is taken into account in studies designed to assess changes in cattle feed efficiency and GHG emissions. More specifically, it illustrates the sensitivity of results to changes in the ruminant milk-to-meat production ratio. It aims to answer the following question: Do the conclusions derived at the animal and farm levels still hold at the higher scale of the country and the world and if not, how can the discrepancies be interpreted?

Assessing feed efficiencies and climatic impacts at the animal and farm levels: The positive aspects of specialisation

At the animal level, increasing cattle production potential – milk or meat – improves feed efficiency and reduces climatic impacts

Ruminant feeding has long been modelled to estimate feed intake and nutritional supplies and requirements. These models are useful for carefully rationing ruminants, taking into account the crucial role of microbial digestion in the rumen. Even though these models of energy supplies and requirements are regularly reviewed (e.g., NRC, 2001, 7th revision; INRA, 2018, 6th revision), they have remained broadly stable. For example, changes in the INRA model mainly took better account of digestive interactions, notably those linked to the level of intake. Based on advancing knowledge in animal nutrition, these models have been used to quantify feed efficiency improvements associated with the dilution of maintenance costs induced by productivity increases. Today, they are also used for assessing GHG emissions from enteric fermentation and manure management, applying the TIER 2 methodology developed by the IPCC based on net energy systems (IPCC, 2006).

Any increase in the milk production potential of dairy cows tends to dilute the share of maintenance expenditure in total expenditure (maintenance and production). Many authors have used this dilution argument to show the value of increasing milk productivity in order to reduce methane emissions (Capper et al., 2009). This dilution effect makes it possible to increase milk production per unit of energy or per kg of feed DM, and to decrease methane emission per kg of milk (Fig. 1). At the animal level, the increase in milk production per dairy cow seems to be the main factor to be considered to both improve feed efficiency and decrease methane emissions per unit of milk.

Likewise, increasing carcass weight of slaughtered animal (kg/-head) allows the dilution of the energy maintenance cost of young beef cattle, essentially because this strategy accelerates the growth of animals. The calculations of feed efficiency and methane emissions are more complex for meat production than for milk production because several growth phases occur, from birth to slaughter. Furthermore, they are generally implemented through different livestock systems. Capper (2011) calculated this dilution effect for beef systems in the United States. She found that the maintenance cost in total energy requirements decreased from 53% in 1977 to 43% in 2007. In general, the improvement is smaller than for milk production, because the daily maintenance cost of beef cattle with high growth rate is higher since the animals are heavier.

Over the last decades, many countries have increased milk production per dairy cow, notably thanks to efficient genetic selection targeted on this trait but also through improved management practices. Meanwhile, average carcass weight of slaughtered cattle (both from dairy and beef herds) has increased, also thanks to genetic selection and improved management. This is illustrated by the increase over time of both productivities in developed countries where they have increased by a factor of between 2 and 4, depending on the country, from 1961 to 2019 (Fig. 2). The trend is most often linear (Australia, Canada, France, United States), although some countries (e.g. Germany) put more effort into milk, producing a curvilinear trend. However, a few countries did not follow this general increasing trend for both milk and meat productivities. New Zealand is probably the best example where production levels per animal remain low today compared to other countries, and where a complex evolution over time has occurred, with first an increase in carcass weight but not in milk productivity, and then, from the 2000s onwards, an opposite evolution.

Increasing milk production per dairy cow and carcass weight per head of slaughtered beef cattle is not the only lever that can be used to improve feed efficiency. Acting on the whole lifetime of animals is also important. Increasing the milk potential over the whole lifetime of dairy cows is a priori advantageous, as fewer

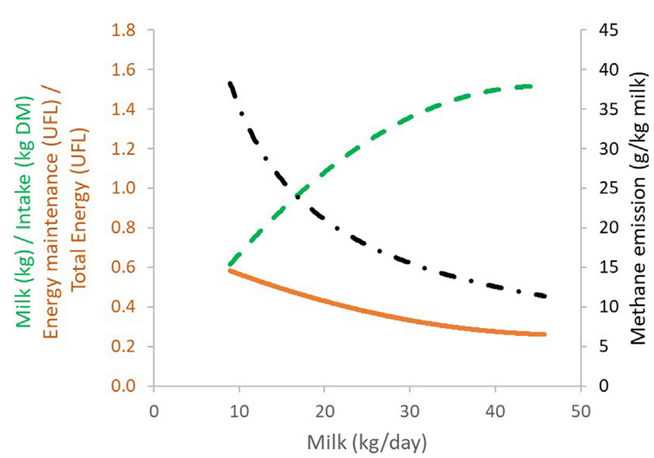

Fig. 1. Simulated impacts of an increase in cattle milk production potential on the share of maintenance needs in energy requirements (————), on milk production per kg of DM intake (– – – –), and on methane emissions in g/kg of milk (- - -). Simulations based on the INRA 2018 modelling framework (INRA, 2018).

replacement heifers are needed to achieve the same milk production. This argument can, however, be challenged by some biological side effects of high-producing dairy cows on fertility and health. Recent studies on milk perturbations in the lactation curve – a good indicator of animal resilience and health – show that higher milk productivity levels are positively correlated with increases in lactation curve perturbations (Berghof et al., 2019). At the herd and farm levels, these effects lead to higher culling rates and then to higher numbers of replacement heifers (Mackey et al., 2007). In addition, increasing milk or meat productivity for feed efficiency reasons involves changes in feed diets that should include (more) energy-rich and highly digestible forages. It is also necessary to increase the proportion of concentrated feeds (grains, oilcakes, co-products) that are generally less rich in cellulose than forages and whose presentation in agglomerated ground-form allows higher intake levels. Depending on the climatic and environmental impacts of these different types of feed ingredients, changes in feeding management may counterbalance the positive effect of feed efficiency increases.

At the farm level, dairy specialisation may improve feed efficiency and reduce the carbon footprint

At the farm level, it is possible to consider not only performance in milk production and carcass weight but also the impacts of health, reproduction, longevity, and feeding systems. As farms are generally not self-sufficient, it is also important to consider farm inputs in any assessment of feed efficiency and/or climatic impacts.

Life cycle assessment (**LCA**) is designed to consider the climatic impacts of a product over its entire life cycle (i.e. not only those stemming from emissions on the farm but also those related to the use of the various inputs required for production). The LCA methodology has been recommended by the FAO in its guidelines for assessing the climatic performance of large ruminant supply chains (FAO, 2016). However, this approach poses implementation problems linked to the allocation of inputs, and thus of climatic impacts, to the different co-products when there are joint productions, which is the case for milk and meat in most dairy systems. Attributional LCA (**ALCA**) describes inputs and emissions within a system by attributing them to either milk or meat. In the ALCA approach, different methods have been developed to attribute inputs and emissions to the different functional units, here, the milk and meat products (Cederberg and Stadig, 2003). Economic allocation consists in assigning inputs and emissions proportionally to product values. Considering the data available, the economic allocation is the easiest method to apply. However, Standard ISO 14041 (1998) generally advises against using this method because the links between inputs or emissions associated with each product and their economic value are generally weak. A preferred approach involves attributing inputs and emissions to the different biological processes required to produce either milk or meat (IDF, 2015). For example, during the rearing period of heifers, all impacts due to inputs and emissions are attributed to meat, whereas during the lactation of cows, impacts are attributed to milk and meat proportionally to energy requirements (which generally means that most impacts are allocated to milk with high-producing dairy cows).

A majority of LCA studies conclude that increasing milk productivity of dairy cows allows the reduction of the carbon footprint of milk. In spite of higher use of concentrates, increasing health problems and decreasing reproduction performances, total GHG emissions (in CO_2 equivalent) per kg of milk decrease with milk productivity. For example, by comparing different German dairy farms with Holstein-Friesian or Fleckvieh breeds, Zehetmeier et al. (2014) reported a significant decrease in the milk carbon foot-

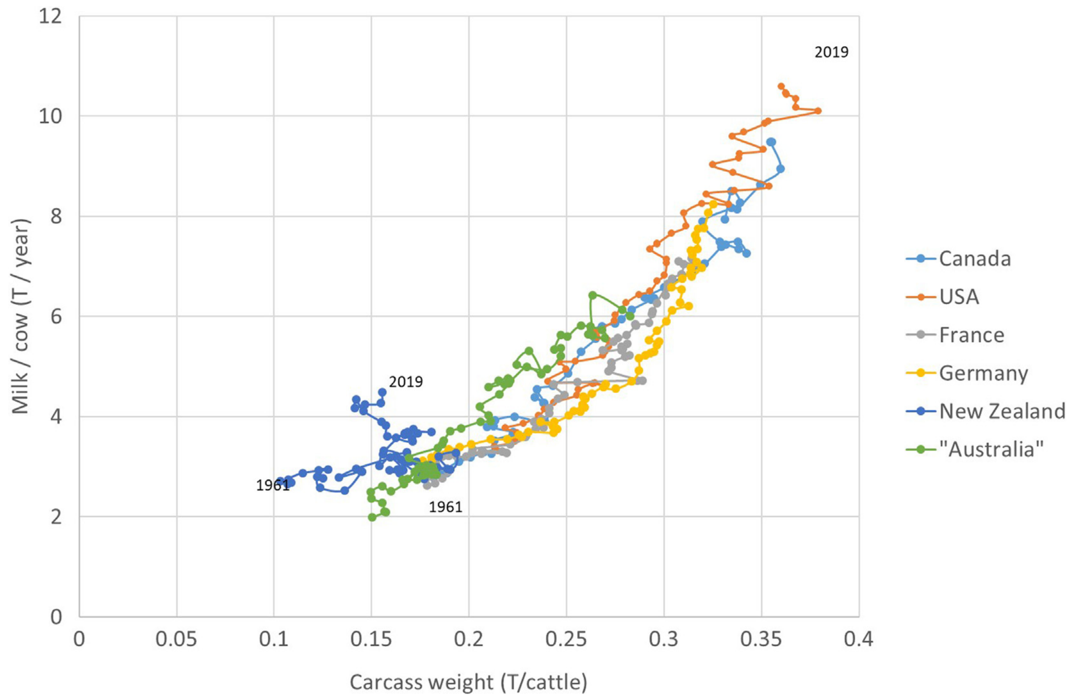

Fig. 2. Evolution of carcass weight per head of slaughtered cattle and of milk production per dairy cow in the 60 last years (1961–2019) in different developed countries. Source: FAOStat.

print as milk production per cow (per lactation or per day of live) increases. This effect was observed both within and between breeds. Comparing dairy farms in 45 dairy regions in the world from the International Farm Comparison Network database, Hagemann et al. (2011) reached similar conclusions, even at high levels of milk yields. These results based on the ALCA approach with a biological allocation of emissions for milk and meat are in line with the general trend identified by Gerber et al. (2011) from the FAO database for different countries in the world using an LCA approach and a protein mass allocation for milk and meat.

For their part, Nguyen et al. (2013) in the case of France and Mogensen et al. (2015) in the case of European Nordic countries compared the carbon footprint of meat produced either from dairy herds and farms or from specialised beef cattle herds and farms. They concluded that the impact of 1 kg of beef meat (slaughter weight) on global warming was significantly lower for meat from dairy calves than from suckling cattle (respectively 16.0–19.9 versus 27.3 kg CO_2 equivalent). This important climatic co-benefit of meat produced in dairy systems is very often neglected in the literature.

However, when dairy systems produce more milk per cow, they usually also produce less meat per kg of milk (Zehetmeier et al., 2014). More precisely, high-producing dairy cows decrease meat production from the dairy herd through three mechanisms. First, fewer animals are needed to produce milk. As a result, fewer calves and fewer animals from the dairy sector are slaughtered. Second, the numerical productivity of cows present (number of calves produced per 100 cows present) tends to decrease as the calving interval increases because of the negative genetic correlation between the milk production level and calving interval traits (Berry et al., 2014). This lengthening of the lactation period may improve efficiency at the scale of lactation by lowering the share of the dry period in the total duration of the lactation. However, this benefit is offset when the effects of lower meat production from the dairy herd are included (Lehmann et al., 2019). Third, the low meat value of the males produced by dairy cows (veal calves or animals of low carcass value that may even be nil for some breeds such as the Jersey) further reduces total meat production. It is worth noting that the second mechanism linked to calving intervals can be offset by using sexed semen and inseminating dairy females with meat breeds to increase meat production from the dairy sector (Doreau et al., 2015). A scenario of sexed semen simulated with Swiss (Probst et al., 2019), Scottish (Eory et al., 2014) and German (Brade et al., 2015) data allowed the reduction in total GHG emissions while maintaining high-producing dairy cows.

In sum, increasing milk production per cow in specialised dairy systems tends to improve feed efficiency and reduce the carbon footprint of milk at both the animal level and farm level. However, this increase is associated with a decrease in meat production from corresponding farms, all other things being equal. As the carbon footprint of meat from dairy calves is lower than that of calves from suckling cows, it is not possible to conclude on the benefits of specialisation at the country and world scale to achieve the same levels of milk and meat productions. To upscale the conclusions derived at the animal and farm levels, it is necessary to consider how the meat production deficit is filled by other systems (usually specialised beef holdings relying on cow-calf and feedlot systems), assuming that cattle meat demand and thus production remain constant.

Are the benefits of specialisation on feed efficiency and global warming obtained at the animal and farm levels confirmed at higher scales (country, world)?

From farm to country level

To analyse the combined effects of cattle milk and meat production at the country and world scale, we propose to examine three approaches. The first consists of adding the effects observed at the farm scale with LCA approaches for different farm types to rebuild the global product equilibrium. The second approach consists in modelling the country as a large cattle herd with the different parameters for the different breeds derived from national statistics. The last method consists in analysing observed data to see how specialisation and GHG emissions have evolved during the last decades.

Adaptation of life cycle assessment

To upscale the effects of specialisation at higher levels than farms, it is important to take into account the consequences of the decrease in meat production from dairy systems. Consequential LCA (**CLCA**) was proposed to estimate changes in input use and emissions within a system in response to a change in the output of a product (Thomassen et al., 2008). Within the CLCA approach, when the milk-to-meat production ratio at the farm level increases, the comparison of different systems allows us to consider how missing meat will be produced to maintain the milk-to-meat production ratio at its initial value. The CLCA approach thus requires changes in the system boundaries, generally by expanding them to maintain the same production levels (in our case, milk and meat productions). In the case of Sweden, Flysjo et al. (2011) concluded that the benefits on GHG emissions linked to higher milk yields per cow disappeared when the expanded system was considered. Zehetmeier et al. (2012) compared the climatic impact of an increase in milk production per dairy cow based on either ALCA or CLCA. The CLCA approach, which expands the system boundaries, suggested that dairy cows producing 6 000 kg or 8 000 kg milk per year emit less GHG than those producing 10 000 kg milk per year, while the ALCA approach, limited to the boundaries of the dairy system, led to the opposite conclusion. Both studies concluded that the reduction in the milk carbon footprint due to specialisation observed at the dairy farm level was not recovered at higher spatial levels because of the higher proportion of meat produced by cow-calf systems.

Modelling approaches

To understand the impact of different milk and meat production scenarios at a national scale, it is again useful to rely on models. In the case of France, Puillet et al. (2014) developed a demographic model of different cattle breeds with their associated production levels and GHG emissions. This model allowed simulation of the impacts of different scenarios on feed efficiencies and GHG emissions, while respecting the livestock demographic constraints and maintaining constant milk and meat production levels. In that perspective, Table 1 illustrates the impacts of a 20% increase in milk production per cow (M+) of Holstein breed with (R−) or without (R=) change in numeric productivity. GHG emissions are stable (+0.5% in the scenario M+R-, −0.8% in the scenario M+R=-) compared to the reference scenario (situation in 2010), in spite of large variations between the different types of cattle. A similar analysis was conducted in Switzerland with a simpler model (Probst et al., 2019). It concluded that moving towards increasingly high-producing dairy cows rather than keeping lower-producing dairy cows but with a better meat value (Simmental in Switzerland) did not improve total feed efficiency or GHG emissions.

Martin and Seeland (1999) developed a theoretical model to analyse the effects of different genetic selection strategies taking into account the genetic correlation between traits. In each scenario, the number of beef cows was adjusted to compensate for the meat production variation from dairy systems to maintain the total meat production (like in CLCA). They concluded that genetic progress achieved through milk or meat specialisation made it possible to increase the animal performances of both dairy cows and beef cattle, and, in some cases, to reduce feed consumption per kg of milk or kg of meat. By contrast, although specialisation slightly reduced the total number of animals (by 2–3%), it did not make it possible to reduce total methane emissions, which could even slightly increase in some scenarios because of higher emissions from the beef cattle herd.

To maintain the cattle milk-to-meat production ratio unchanged, an increase in dairy cow productivity must be compensated for by a simultaneous increase in the number of beef cows with, as a result, an ambiguous effect on total methane emissions (and more generally, on total GHG emissions).

Analysis of the French case over the past decades

To validate the previous conclusions based on either CLCA or modelling, it is interesting to examine the case of a country with a practically constant ratio of cattle milk-to-meat production during several decades. Over the past few decades, most countries have experienced a large increase in milk production per cow (Fig. 2). Meanwhile, numerous countries have seen their bovine milk-to-meat ratios change over time. However, in other countries, this ratio has been more or less constant. Over the period 1961–2019, several countries such as Germany, the Netherlands and New Zealand made the choice of dairy specialisation with a very high milk-to-meat production ratio increasing from about 15 to about 30 kg milk/kg carcass. By contrast, in other countries such as France, this ratio has remained much more stable.

France is thus an interesting case to consider because it has had a stable milk-to-meat ratio since the introduction of dairy quotas in 1984. Table 2 depicts the French situation over the period 1990–2005. On average, milk production per dairy cow increased by 89 kg per year, whereas the carcass weight of slaughtered animals increased by 0.6 kg per year. This increase in milk potential of

Table 1
Direct greenhouse gas (GHG) emissions of French cattle livestock associated with scenarios of different milk potentials for dairy cows (M+R= and M+R-) simulated with the CANAPOM model (adapted from Puillet et al., 2014).

		REF[1]	M+R=[2]	M+R-[3]
Total population	Mt CO_2eq	55.1	54.7	55.4
	% variation w.r.t. REF	–	−0.8	0.5
Dairy cows	Mt CO_2eq	16.7	15.4	15.4
	% variation w.r.t. REF	–	−7.9	−7.9
Other dairy cattle	Mt CO_2eq	8.8	8.0	7.6
	% variation w.r.t. REF	–	−9.6	−14.1
Beef cows	Mt CO_2eq	16.1	17.1	17.7
	% variation w.r.t. REF	–	+6.0	+9.8
Other beef cattle	Mt CO_2eq	13.4	14.2	14.7
	% variation w.r.t. REF	–	+5.5	+9.3

Abbreviations: Mt = million tonnes; CO_2eq = CO_2 equivalent; w.r.t. = with respect to.
[1] REF: Reference year 2010.
[2] M+R=: Scenario with a 20% increase in annual milk yield of Holstein cows (9 295 kg/cow/year) without change in reproduction.
[3] M+R-: scenario with a 20% increase in annual milk yield of Holstein cows (9 295 kg/cow/year) with a simultaneous decrease in numeric productivity due to longer lactation and lower fertility.

Table 2
Evolution of bovine milk and meat production (Eurostat) and associated greenhouse gas emissions (GHG) in France from 1990 to 2005 (CITEPA).

Year	1990	1995	2000	2005
Milk production (1 000 t)	25 702	25 413	24 929	24 675
Meat (1 000 t carcass equivalent)	1 843	1 820	1 846	1 827
Milk-to-meat ratio(t/t)	13.9	14.0	13.5	13.5
Number of cattle (1 000 heads)	21 401	20 540	20 310	19 310
Total cows (1 000 heads), including	9 012	8 655	8 517	8 026
- Dairy cows (1 000 heads)	5 303	4 516	4 203	3 958
- Beef cows (1 000 heads)	3 708	4 139	4 314	4 068
Milk production per dairy cow (kg/year)	4 846	5 627	5 932	6 235
Meat production per head of cattle (kg carcass equivalent/year)	86.1	88.6	90.9	94.6
GHG emissions (CH_4 and N_2O)				
- Total (1 000 t CO_2eq) [1]	49 688	48 350	49 706	46 277
- Total bovine CH_4 (1 000 t)	1 448	1 407	1 451	1 357
- Total bovine N_2O (1 000 t)	45	44	45	41
- per t of milk (t CO_2eq)[1] (without allocation of CO_2 for meat)	1.93	1.90	1.99	1.88
- per t of meat (t CO_2eq)[1] (without allocation of CO_2 for milk)	26.9	26.6	26.9	25.3
- per head of cattle (t CO2eq)[1]	2.32	2.35	2.45	2.40
- per cow (t CO_2eq/cow)[1]	5.51	5.59	5.84	5.77

Abbreviations: CO_2eq = CO_2 equivalent.
[1] Source: CITEPA (national inventory); for CH_4, enteric emissions and emissions linked to manure management; for N_2O, direct and indirect emissions in barns and pasture, as well as emissions linked to the spreading of manure.

dairy cows combined with the introduction of dairy quotas that limited total milk production until the end of this supply control policy from 2015 led to a sharp reduction in the number of dairy cows. This reduction concerned notably the dual-purpose Normande breed, whose numbers fell 6-fold between 1970 and 2010, while the herd decline was only 18% for the Holstein breed. Meanwhile, the number of beef cows (Blonde d'Aquitaine, Charolaise, Limousine) increased substantially with animals of larger formats reared in increasingly specialised holdings (Pflimlin et al., 2009). Genetic selection yielded fast-growing animals with increased carcass weights. Furthermore, the French Livestock Law introduced from 1966 (and modified in 2006) favoured the specialisation of both cattle breeds and livestock systems (Vissac, 2002). Overall, feed efficiencies did not change significantly and methane and nitrous oxide emissions reported in national inventories (CITEPA, 2017) remained almost constant per unit of milk or meat produced (Table 2; Pflimlin et al., 2009; Faverdin and van Milgen, 2019). The French case corresponds to a situation where the increase in the carcass weight of slaughtered cattle did not translate into an increase in meat production per animal at the country level, nor into a significant reduction in total methane and nitrous oxide emissions from dairy and meat cattle breeds. In other words, the gains in efficiency and GHG emissions at the animal level achieved through genetic progress were offset by the lower meat co-production of the dairy herd and the increasing number of beef cattle.

The analysis shift to a national scale shows that increasing milk production per cow is not necessarily the optimal action level for improving feed efficiency and reducing GHG emissions of the whole cattle population, unless meat production (and consumption) is simultaneously reduced. The use of dual-purpose milk and meat breeds does not necessarily increase GHG emissions, and can even be more advantageous in some cases. The choice between the two strategies must also consider additional criteria such as other environmental impacts, the optimal use of land and available feed resources, and the profitability of livestock systems influenced by public policies.

Cattle milk and meat efficiencies in Europe: consequences of variable milk-to-meat production ratios

Cattle production in European countries exhibit very different milk-to-meat production ratios (Fig. 3). Does this variety affect feed efficiencies of cattle milk and meat production? To answer that question, we relied on the works of Hou et al. (2016) and Forslund et al. (2020). To calculate the FCR for both milk and meat at the country level, Hou et al. (2016) developed a method close to the biological allocation method used in ALCA. They considered that the feed consumption of dairy cows could be assigned to milk, and that the feed consumption of all other cattle could be assigned to meat. On this basis, Forslund et al. (2020) calculated DM intake using the TIER 2 method of the IPCC (IPCC, 2006). Inter-country trade of live animals was taken into account.

Fig. 3 presents an application of this approach to European countries based on Eurostat data (Forslund et al., 2020). It shows

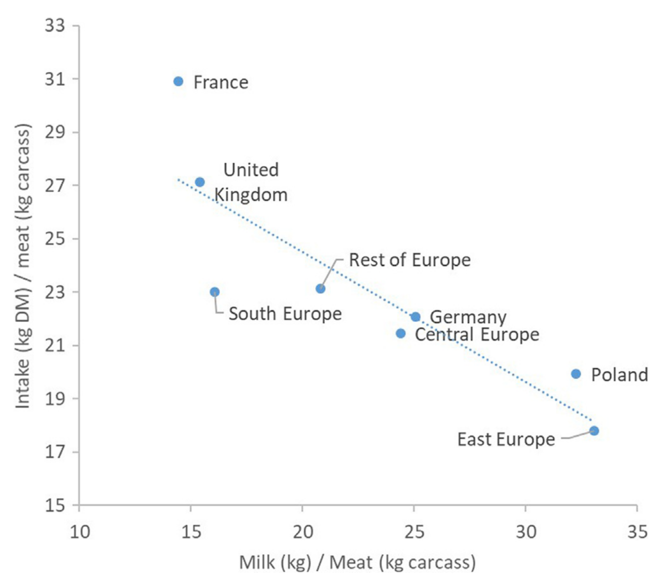

Fig. 3. Relationship between the cattle milk-to-meat production ratio (kg milk/kg carcass) and the Feed Conversion ratios (FCRs) of meat (kg DM intake/kg carcass) in various European countries or groups of European countries[1]. [1]East Europe includes Romania, Bulgaria, Hungary, Serbia; Central Europe includes the Czech Republic, Austria, Slovakia and Switzerland; South Europe includes Spain, Italy, Portugal and Balkan countries except Serbia and Bulgaria; Rest of Europe includes Nordic and Baltic countries, Ireland, the Netherlands, Belgium and Luxemburg. Large exports of live young cattle from France to southern Europe explain the respective distance of corresponding countries from the regression line, by increasing the meat FCR of France and decreasing the meat FCRs of southern Europe. Source: Forslund et al. (2020) from Eurostat data.

that feed efficiency for meat is negatively correlated with the milk-to-meat production ratio. The higher the ratio, the greater the share of meat produced from the dairy herd and the lower the FCR for meat. The feed efficiency of meat is improved because less feed consumption by breeding females is attributed to meat. Fig. 3 also shows that countries (like France) that export many young live animals do not fully recoup the feed cost associated with the cow-calf system, which tends to increase their meat FCR for the benefit of importing countries (southern European countries and North Africa in the case of France).

Countries that have chosen to increase milk production more than cattle meat production thus have lower GHG emissions per kg of cattle meat due to its lower FCR. However, if domestic meat consumption is not fully covered by domestic production and therefore requires increases in meat imports, the result is mainly a transfer of GHG emissions between countries. The model of Puillet et al. (2014) allows the simulation of GHG emission changes when milk or meat production levels vary relatively to the base period situation. For France, which was roughly self-sufficient in milk and meat in the 2010 base year used to calibrate model parameters, it was possible to simulate the consequences of a change in the milk-to-meat production ratio with the same farming systems but with varying proportions of milk or meat. The two scenarios, corresponding to (i) a change in milk production while keeping meat production unchanged and (ii) a change in meat production while keeping milk supply unchanged, yielded similar results for GHG emissions. In both scenarios, an increase in the milk-to-meat production ratio from 11 to 15 kg of milk per kg of carcass weight decreased GHG emissions of one kg of cattle carcass of 6%. This is the result of a larger proportion of meat produced from the dairy sector that requires less feed than the beef sector to produce meat. It is important to underline that these calculations do not integrate impacts on GHG emissions associated with land use changes or with any compensation on food consumption of other products. When the decrease in cattle milk or meat production allows the release of grasslands that are then used for crops or urbanisation with, as a result, lower carbon storage in agricultural soils, the gain in total GHG emissions is reduced. Furthermore, biodiversity losses can be significant.

Cattle milk and meat feed efficiencies in the world: Contrasted situations depending on milk-to-meat production ratio and milk productivity

Milk-to-meat production ratios are much more variable in other regions of the world than in Europe. In 2010, this ratio varied between 3 and 35 kg milk per kg carcass meat produced. Many countries and regions, notably in America, Africa and Oceania, had a ratio lower than 15 kg of milk per kg of meat carcass, which was the minimum in Europe. Because of specific religious observances concerning cattle meat, India is a particular case. It exhibits a marked imbalance between milk and meat productions, with a ratio of 100 kg of milk per kg of meat carcass.

Milk production per dairy cow has followed an upward trend in almost all countries over the last decades. According to our calculations based on FAO data, between 1995 and 2015, it increased linearly by 1% to 3% per year almost everywhere, except in Africa where it did not rise significantly. However, since base period levels and increase rates were different, dairy cow productivities were still very heterogeneous in 2015, ranging from 270 kg per year in West Africa to 9 440 kg per year in North America. In that zone, where the dairy cow productivity today exceeds 10 000 kg per year, milk productivity is still growing by a little more than 1% per year (the same growth rate as in Europe). 40 years ago, Kennedy (1984) forecasted that milk production per dairy cow would continue to increase for a long time, a prediction that has been confirmed by figures until now. Genetic and technical management limits to dairy cow productivity are difficult to appreciate due to important genetic and environmental interactions (Horan et al., 2005). However, estimates of GHG emissions in different parts of the world suggest that there is no clear climatic profit in increasing dairy cow productivity beyond about 4 000 kg milk per year (Gerber et al., 2011).

During the same decades (1995–2015), still according to our calculations based on FAO data, meat production per head of cattle increased very slowly compared to milk production per cow, with a world average annual rise of only 0.5%. If meat production per head of cattle increased by more than 1% per year in Brazil, North Africa and the Near and Middle East, it stagnated or decreased in other parts of the world. In North America, where this indicator is the highest, there was no clear increase between 2000 and 2015. Contrary to milk productivity, it seems that there is a ceiling to meat production per head of cattle. The low numerical productivity of the cattle herd is the first factor that limits the possibility of further increasing meat production. Unlike some other animal species, fecundity cannot exceed one calf per cow per year, which requires a high proportion of reproductive cows in the total herd compared to growing animals.

Large variations between countries in milk and meat productivities in the world are associated with a very broad range of feed efficiencies (Forslund et al., 2020). Fig. 4, which plots beef meat production per non-dairy cattle (cattle other than dairy cows) against milk production per dairy cow in different regions of the world in 2010, reveals a divide between countries with low versus high dairy cow productivities. In countries where milk productivity is low (less than 4 000 kg/cow/year), meat production per head of non-dairy cattle is also low (positive spatial correlation between the two productivities). In these regions, both milk and meat productivities have tended to increase over time, probably under the effect of improved production factors (use of feed resources of higher quality, better health management). In regions where milk production per dairy cow is high (more than 4 000 kg/cow/year), the higher milk productivity, the lower meat production per head of non-dairy cattle (negative spatial correlation between the two productivities). Two regions, North Africa and the Former Soviet Union, appear specific with low milk productivity but high meat production per head of non-dairy cattle. This could be explained by the fact that in these regions, cattle meat is almost totally produced from the dairy sector.

As part of a recent study aimed at assessing cropland and grassland needs by 2050, Forslund et al. (2020) evaluated the consequences of these discrepancies on feed efficiencies of bovine milk and meat production. As shown in Fig. 5, the milk and meat FCRs calculated for 2010 exhibit patterns similar to those of Fig. 4. In countries where milk and meat productivities are low (mainly developing countries), a higher milk productivity is accompanied by a joint improvement in feed efficiencies for both milk and meat. By contrast, in regions where milk production per cow is high (except in North Africa and the Former Soviet Union), there is a trade-off between milk and meat feed efficiencies to the extent that an improvement in milk feed efficiency is accompanied by a deterioration of meat feed efficiency. This last finding is consistent with observations for Europe presented previously.

To increase milk production per cow, genetic selection is not efficient without better management practices. There is a positive correlation between milk productivity levels and the proportion of quality roughage (forage crops) in total intake of roughage (Fig. 6). Unexpectedly, the proportion of concentrated feeds does not appear to be a significant factor in explaining milk productivity differences between countries. In regions where milk and meat production levels are low, any increase in productivity and production will most likely have to be accompanied by increased

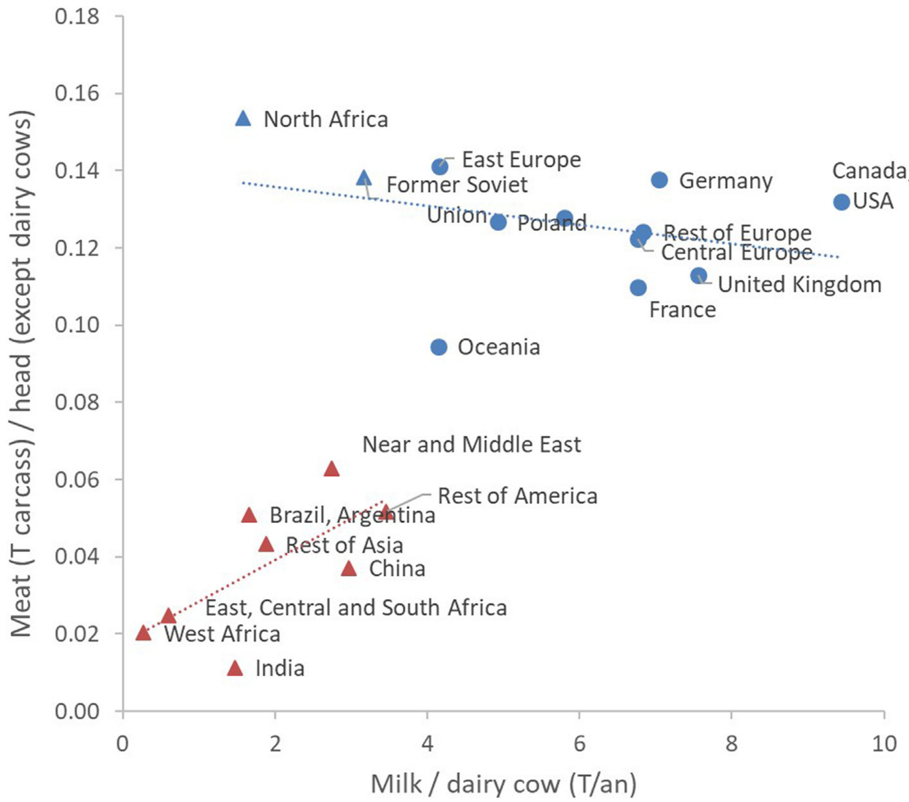

Fig. 4. Beef meat production per head of cattle (excluding dairy cows) and milk production per dairy cow in different countries and regions of the world in 2010 (adapted from Forslund et al., 2020, from FAOStat data). Triangles correspond to countries/regions with milk production per dairy cow lower than 4 000 kg/year, and circles to countries/regions with more than 4 000 kg/year. The blue colour indicates countries with high cattle meat production per head (more than 90 kg carcass/head of cattle excluding dairy cows) and red colour to countries with low cattle meat production per head (less than 90 kg carcass/head of cattle excluding dairy cows). Countries and regions in red suggest a positive relationship between the two indicators when both are low. Countries and regions in blue suggest a negative trend between the two indicators when they are high.

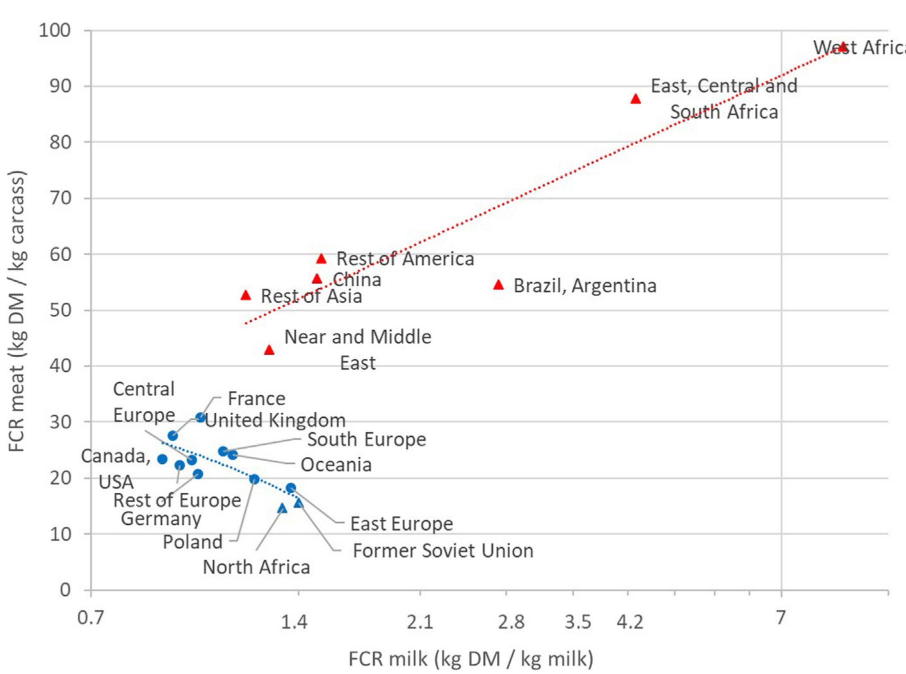

Fig. 5. Feed conversion ratios (FCRs) for cattle meat (DM intake kg/kg carcass) and cattle milk (DM intake kg/kg milk with a log scale) in different countries and regions of the world (adapted from Forslund et al., 2020). The symbols and colours are the same as in Fig. 4. Countries/regions in red with low milk and meat productivity levels show a positive relationship between the milk and meat FCRs, while countries/regions in blue exhibit a negative relationship between the two FCRs.

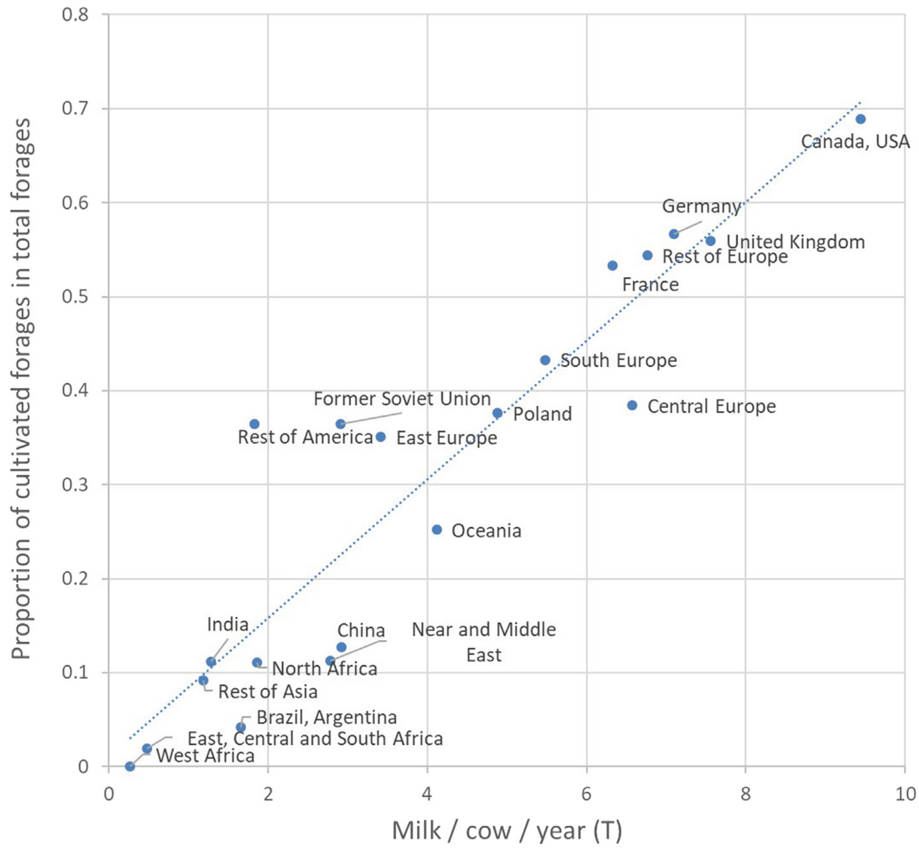

Fig. 6. The proportion of cultivated forages in total forages in different countries and regions of the world increases with milk production per dairy cow (year 2010) Adapted from Forslund et al. (2020).

production and consumption of quality forages (Bouwman et al., 2005; Fetzel et al., 2017). Such developments do not necessarily compete with land required for crop production as fodder crops, particularly legumes, can also be used to increase crop yields. In regions with low chemical fertiliser use, introducing legumes in rotation with forages and associated organic fertilisers are important levers for reducing yield gaps in line with agro-ecology principles (Tapsoba et al., 2020). For example, in Africa, future agricultural land needs could not be satisfied without drastic changes in animal and plant productivities, including grass and forage productivities (Tibi et al. 2020). Substantial improvements in animal feed efficiencies are possible, especially if the production of meat and milk from cattle herds becomes as important as manure, capital and power services (which is not always the case today). Increasing investments in small dairy units in Africa to boost the supply of milk food products is a promising avenue for more efficient milk production, as recently described for Ethiopia by Minten et al. (2020).

Conclusion

The specialisation of cattle breeds and livestock production systems towards milk or meat has tended to forget that the two productions are linked. This linkage means that impacts of milk specialisation cannot be accurately assessed without looking at impacts of the associated meat production. It is thus risky to upscale conclusions drawn at the animal and farm levels to the national or world scale without considering dairy and beef herds together. This is illustrated here for feed efficiencies and global warming impacts. At the animal and farm levels, improved animal performance decreases feed use and greenhouse gas emissions per kg of milk or carcass weight, mainly through a dilution of maintenance requirements per unit of product. However, increasing milk production per dairy cow reduces meat production from the dairy sector, as there are fewer dairy cows. To maintain cattle meat and milk production at higher scale, it is necessary to produce more meat from the cow-calf systems, which tends to increase the global warming impact and to decrease feed efficiency of cattle meat. This is due to the higher warming impact of the meat from the cow-calf systems compared to the meat from dairy sector. To avoid a decrease in the feed efficiency of meat when milk productivity of dairy cows increases, it is important to increase the capacity of the dairy sector to produce more meat. Selecting dairy cows on both milk and meat production criteria can be a valuable option, but the use of sexed semen and crossing dairy cows with beef bulls can also be efficient. However, in many developing countries, notably in Africa, increasing productivities of both dairy and beef cattle herds will increase milk and meat efficiencies, reduce land use, and decrease methane emissions to meet the urgent need for sustainable food security in these regions.

Ethics approval

Not applicable.

Data and model availability statement

All the data from FAOSTAT used in the review are available at http://www.fao.org/faostat/en/#data.

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Author contributions

PF, **AF**, **HG** and **LP** discussed the main concepts, literature and together drew up the framework of the review. **PF** was the major contributor to drafting the manuscript; **PF**, **AF**, **HG** and **LP** read, corrected and approved the final manuscript.

Declaration of interest

The authors declare that they have no competing interests.

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