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

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Supplementary Material S1

Importance of cattle meat production a worldwide base.

Cattle meat production is largely distributed over all the Earth's continents (see figure 1) although there is a not negligible difference in the percentage contribution by different continents if considering the number of animals slaughtered or the weight of carcasses obtained. This because Africa and Asia contribute more to the number of cattle slaughtered and less to the total weight of carcasses produced, which means that slaughtered cattle on these continents weigh less than the world average. More than 40% of beef is produced in America, whereas just about 10% is obtained in Africa.
In 2019, China was the country with the largest number of slaughtered cattle, while U.S.A and Brazil produced the largest quantities of beef (figure2) (FAOStat, 2020).

Supplementary Material S2

Beef from dairy farming systems

Opportunities from beef production can derive from animals exceeding the replacement quota in dairy farms. With the use of sexed semen the genetic selection emphasis can be more narrowed and effective indeed, a larger number of beef x dairy crosses can be produced from dairy farms. It might generates a large saving in terms of land and maintenance costs of calf mothers in cow calf-systems or a significant increase in meat production. In Europe the preferred meat breed to cross dairy breeds include the Blue Belgian, Charolais, Limousin, (Vellinga and De Vries, 2018) whereas other breeds are used in Asia and US (Bown et al., 2016). The use of crossbreed beef x dairy to increase meat production was already indicated as convenient strategies both for beef and dairy farming in the earlier 80' pointing out the up to 25% of beef meat proceeded with dairy genes (Cartwright, 1983). The use of dairy mothers to carry beef calves has been in the past underconsidered since the maintenance requirement of dairy breeds are often 10 to 20% higher than beef breed (Cartwrigt, 1983) due to their larger, more metabolically active internal organs (e.g. liver) and fat depots (e.g. omental and mesenteric fat) aimed to support milk yield requirements (Bown et al., 2016). The use of beef semen in current average dairy farms is not suitable because of the high demand for heifers but there could be convenience by combining dairy sexed semen for the best cows and beef semen within the breeding options for the genetically poorer cows in the herd. It may generate advantages in dairy herds if the genetic level of the herd for milk production increases using beef semen in genetically inferior cows, since their offspring leave the milking herd (Ettema et al., 2017). It is particularly true when sexed semen is used on the youngest generations and the breeding strategy is combined with genomic testing (Hjortø et al., 2015; Ettema et al., 2017). The optimal breeding mix depends on the value of the various kinds of calves that could be produced (de Vries et al., 2008) and economic convenience for the dairy herd seems evident with low costs of heifer rearing, improved cow longevity and when the economic benefits from improved genetic level of the herd are included (Ettema et al., 2017). The combination of sexed semen and crossbreeding increased dairy herd profits of average of €79.42 (from 0 to 568 €) per cow per year with a 21.5% of cows inseminated with beef semen and with higher benefits in farms with low stocking rate (Pahmeyer and Britz, 2020). Otherwise, many advantages can be highlighted for beef supply chains. Potentially a large proportion of crossed calves born to double-muscled sires can quantitatively and qualitatively improve beef production (Bittante et al., 2020a). Berry et al. (2019) demonstrates that superior carcass and growth performance can be achieved with the appropriate selection of beef bulls for use on dairy females with only a very modest increase in collateral effect on cow performance (i.e., 2–3% greater dystocia expected and a 6-d-longer gestation length) and affirmed that a dairy-beef index should be also developed to improve system performance. The same authors observed that crossbreeding using beef semen improved the odds ratio of conception in cows by 1.37 and improved the average herd fertility parameters and the sold calves and the values of the crossed calves (Blue Belgian or Simmental x Holstein) were about 3 times higher than purebred Holstein (Bittante et al., 2020b). In European pasture based dairy farm systems combining sexed semen use with conventional beef semen seems to be one of the only strategies allowing herd expansion with additional incomes (Murphy et al., 2016).

Furthermore, it has to be considered that a notable part of beef production in EU-28 derives from the dairy sector (Hocquette et al., 2018). The sector is increasing its specialization pursuing goals of improved efficiency and productivity (Pulina et al., 2020) and the specialization for milk production decreases the dairy contribution to meat in a significant manner especially in Europe. EU-28 accounted for about 23 million of dairy cows in 2019 (Nalon and Stevenson, 2019). From these premises could be speculated that a general 20% of dairy cows that could be inseminated with beef (Pahmeyer and Britz, 2020) and a 80% of successful calving destined to beef market products could be assumed. Then considering a similar growing and fattening cycle and average weights of 550 kg at slaughtering (e.g: Holstein vs. Limousine x Holstein or similar crosses; Vestergard et al. 2019) and increases in slaughtered weight by 9% on average, increases of carcass meat by 16% and increases of processed meat due to differences in dressing percentage 23% (Vestergard et al. 2019) for crossbreed beef–dairy veal in respect to purebred dairy veal a raw estimate of whole gain in beef production in EU-28 could correspond to additional 118,000 tons of carcass weight and meat in the EU-Market with much higher quality and market value. The expected increase in meat production should be much higher at the real system level since often Holstein bulls are slaughtered at very low live weights (<300 kg) whereas crossbred reach higher weights at slaughtering (> 500 kg) and also double muscle breeds are often used for crossbred dairy-beef (Blue Belgian) with additional meat yields, dressing percentages and quality scores with additional economic gains. In Danish systems the economic advantage of this practice leaded the farm to +0.70 € of net returns per d considering in 500 days of the beef growing cycle (Vestergard et al. 2019). More advantages can be highlighted from an environmental point of view. Vellinga and de Vries (2018) stated that pressure on specialization on milk production for economic and environmental purposes might have a side effect related to impacts from beef production. GHG emission intensities of beef produced in pure beef systems are known to be on average 70% higher than those of beef produced in specialized dairy systems mainly because in pure beef systems, all emissions, including those of the maintenance of the suckler cows, are allocated to beef only. As a consequence, compensation of the lower output of beef from dairy production by beef from pure beef systems could contribute to increased GHG emissions from the cattle sector. In fact, specialization from dual purpose systems to milk yield reduction in resource use efficiency should take into account that carbon footprint of milk production decreases with animal production level only if the decrease in beef production is not accounted for. When the milk and meat production level are simultaneously considered, then milk specialization reduces meat production which need to be compensated with an additional number of suckler cows for beef production with general increases of resource use, emissions and production costs (Zehetmeier et al., 2012). Recently, simulations for the New Zealand System demonstrated that integrating dairy and beef production would enable the NZ beef sector to reduce annual GHG emissions by nearly 22% of the total sector's emissions), while the dairy sector would reduce the surplus dairy calves slaughtered from 4-days old with relevant social implications (Van Selm et al., 2021). The same authors stated that the challenge of reducing GHG emissions of milk and beef production requires an integrated approach, beyond the system boundaries of the dairy and beef farms. In this sense the increase in beef production from intensively managed dairy farms could be a valuable solution to be considered in association to the diffusion dual purpose breeds in mixed systems (Vellinga and de Vries, 2018).

Generally, more crossbred calves for beef production may be produced thus increasing meat production and supply. Otherwise, a market for these crossbred calves is not well established (de Vries et al., 2008) and limits are also represented by quality scores evaluations, market values and consumer acceptance. A broad review on beef x dairy crosses states that beef of dairy origin is generally considered inferior to beef produced from traditional specialized beef breeds (Bown et al., 2016). The same authors stated that this belief is not supported by the scientific literature which suggests there is no difference between dairy and traditional British beef breeds in growth potential, lean meat yield, yield of prime cuts, and the quality of meat produced when grazed under similar conditions and slaughtered at the same chronological age or the same level of maturity. Indeed, there was no difference between dairy and British beef-bred animals in the yield of higher value primal cuts as a proportion of carcass weight even if classification grades penalizes crossed beef vs. purebred meat (Muir et al., 2000). Recent evidences could justify adjustments in the classification grades and also enhancement of crossed beef x dairy productions (Bown et al., 2016).

Supplementary Material S3

Open and close production cycles: principal operation in different countries.

-Cow-calf operations

In Europe the segment of the beef supply named as cow-calf (of agricultural nature) is mainly carried out in small-medium sized farms whose main dimensional limitation is the availability of land and the carrying capacity for cattle. These are in the mountain and hill areas, mostly breeding local breeds or their crosses with specialized beef breeds (as Charolaise and Limousine among others), where animals graze all year, especially in Mediterranean area. Herd is mainly raised on pasture (with limited feed supply) in order to produce and to sell weaned calves (at 6-9 months of age and at 200-300 kg of live weight) to fattening farms, which will complete the beef production cycle (Piedrafita et al. 2003; Ligios et al. 2005; Blanco et al. 2017; Gourdouvelis et al. 2019). However, grassland typically used in beef-farms occupies land areas not suitable for production of concentrate feed for livestock, or feedstuffs for humans. Hence, the cow-calf system relies on the cow's ability to exploit the pasture resources, in some instances of low quality and in some period also

low availability (Henkin et al. 2011). The rationale for these grass-based production systems is the lower comparative cost of grazed grass as a feedstuff together with its (potentially) high nutritive value (McGee et al. 2014). In this scenario, even if the beef cattle systems vary enormously across countries in terms of herd size, stocking density and level of output, the productive efficiency of every cow is essential to the biological and economical sustainability of this livestock system. In both calf-to-weaning and calf-to-beef systems the feeding of suckler cow is a relevant cost.
In USA beef cattle farming is widespread throughout the territory, although there are significant differences between States. in fact, most of the cow-calf herds are raised in the central regions, characterized by abundant natural pastures alternate with cultivation of grains such as soybeans, corn and other cereals. Cattle herds are also important in the south-eastern States, where the animals are raised using improved pastures, while in the western states veal cattle breeding is strongly localized in federal pasture areas that are granted to cattle breeders. These orographic, environmental and climatic differences of USA lands lead to use a wide geno-phenotypic variety of cattle to better exploit the forage resources of the different territories: it is estimate that about 80 beef breeds are reared in the United States today (Drouillard, 2018). However, approximately 60% of slaughtered cattle originates from crossbreeding (Field, 2018) with a clear predominance of breeds of British origin, whereas the increasing use of continental European breeds and the large presence of the crosses between *Bos taurus* and *Bos indicus,* in the hottest regions of the country. Field (2018) reported that in 2015 in USA about 80% of cow-calf farms are medium-smallsized, with fewer than 50 head of cows, contributing for less than 30% of the national inventory; only 10% of cow-calf farms have more than 100 cows, representing about 55% of USA bovine herd.
In Latin American countries the cow-calf phase is generally managed extensively on large farms where herds are fed on native pastures and grasslands. However, in recent decades, increasing pressure to use arable land for grain production, particularly soybeans, has pushed this farming system to areas with less productive land (Nin-Pratt et al., 2019). In temperate areas the target of the herd management is for spring and early summer calving of cows remaining on pasture year-round. In tropical pastures, particularly in Brazil, the cow calf phase is largely supported by application of industrial crosses where *Bos indicus* cows are mated with European beef (Millen et al., 2011).
Australian and New Zealand beef production are based on pasture and rangeland cow-calf systems. A relevant aspect of beef supply system in New Zealand is that cattle herds, and beef cows in particular, are usually farmed with sheep flocks in the steeper hill country often of lower fertility (Morris and Kenyon, 2014; Kaurivi et al., 2020). Greenwood et al. (2018) in their recent review of the Australian beef production system well highlight how there are important differences between farms with respect to their geographical and therefore climatic location. In fact, the beef production in South Australia largely uses native temperate pastures and the more marginal lands are used more for beef cows herds. Cows are programmed to calve at the most favorable times for grazing, according to the rainy seasons. Calves are typically weaned at 200-300 kg (4-9 months old) and reared on pasture. British breeds, particularly Angus and Hereford, have been predominant and large European breeds, such as Charolais, are used as terminal bulls to increase the carcass weight of slaughtered animals. The Northern Australian beef farming is generally characterized by lower stocking rates on larger properties, because of the limitations in terms of soil productivity and climatic conditions. In these districts, the tropically-adapted *Bos indicus* genotypes have a higher proportion than *Bos taurus*, being the major breeds Brahman, Santa Gertrudis and Droughtmaster to exploit the advantages of *Bos indicus* cattle in terms of tick resistance and heat tolerance.
As previous mentioned, a relevant share of calves entering in the beef supply comes from dairy cow herds: they are males and females exceeding the replacement. In dairy farms the chance of calves is conditioned by several management and economic opportunities, such as the price of milk and the costs of feed milk replacers. The contribution of dairy calves to the beef production is very low when they are slaughtered a few days of age (bobby calf) (Morris, 2013).In other cases, these animals are used to the production either "White"veal (calves slaughtered at less than 8 months of age and fed low-iron and low fibre diet) or "Rosé"veal (mostly male dairy calves raised on a diet including roughage and concentrates and slaughtered at approximately at age of 6 to 12 months; Pardon et al. 2014). In other conditions, the male dairy calves are managed in calf-to-beef system to obtain steers. Veal production is important in Europe and in particular in certain countries such as Netherlands, France and Italy (Skelhorn, et al. 2020). The different production systems of veal in European countries are reviewed by Domaradzki et al. (2017).

-Backgrounding and finishing operations

In the beef production system, weaned calves can be managed, and always fed, on pasture until they reach slaughter weight/age or handled for the finishing phase in feed-lots. The first system is still used in areas where plentiful pasture and/or grassland all year round is available as fed for these cattle, such as in several regions of North and Central-South America, Australia and New Zealand. However, the increasing pressure to use these fertile soils for crops is limiting this possibility even in those regions where traditionally slaughtered cattle were fed on pasture (Greenwood et al., 2018; Morris and Kenyon, 2014; Nin-Pratt et al., 2019).

In segmented beef production systems, i.e. where calves from their birth until they reach slaughter weight change ownership, the operations of backgrounding lots and/or feedlots are decisive. In those systems the weaned calves, which typically are 5-7 months age and their weigh is about 180-260 kg, can transferred in stocker facilities for stocker (grazing) or backgrounding (dry-lot) phase before of the finishing phase. During this intermediate phase, between weaning and the final phase in feedlot, weaned calves fed a combination of high forage, such as pasture or dry-diet, and low grain rations since the aim is to maximize the growth and minimize the fat deposition. This breeding stage is commonly used in North and South America, Australia and New Zealand but much less so in Europe.

The feedlot is the true intensive production phase (of industrial nature) that aims to grow and/or fatten cattle to slaughter weight. Its duration depends on the weight and age of the incoming animals and the level of finishing required, understood as weight and fat cover, for slaughter. Cattle finishing in feedlot, albeit limited to the last 2-3 months before slaughter, is also being adopted with increasing interest in beef production systems traditionally based on the use of large pasture areas such as in South America (Millen et al., 2011) and Australia (Greenwood et al., 2018).

Typically, feedlots for backgrounding and feeding operations are confined areas that are: an open lot (such as when animals can stay in open condition along the year), open lot with barn (shelter), or total confinement in barn (when the climate condition isn't comfortable for cattle in fattening phase). Custody cattle in indoor facilities has the function of keeping not only the cattle but also the feed and bedding dry and in some cases the slated floor permits that manure fall into collection pits. Typically, these types of feedlots are smaller in size and contain fewer cattle per pen, although they have a higher stocking density than open-air feedlots. The way in which cattle is reared in feedlots has several implications of absolute importance for the management of manure or wastewater that have a significant impact on productive costs, animal welfare and environmental impact of farming.

Steers, bulls and heifers are usually fed by total mixed ration, consisting of high rate of concentrate (mostly cereals) and low of roughage (mostly corn silage): according to market demands and breed reared, the calves are slaughtered at different age (14-18 months) and live weight (450 700 kg) (Zjalić et al., 2006; Cozzi, 2007; Matthews and Johnson, 2013).

Cattle comfort can be also considered within management practices. Shade can reduce negative effect of rain and wind, mitigate heat stress from solar radiation (Hayes et al., 2017). Mitlöhner et al. (2001) found that shaded heifers had greater dry matter intake (DMI) and greater average daily gain (ADG) compared with unshaded ones, shorter fattening cycles reduced social competition and fighting.

Supplementary Material S4

Non feeding approaches to reduce GHG emissions at farm level in beef industry.

-Enhancing animal performances

The single most effective strategy to reduce GHG emissions per unit of meat produced is enhancing animal productivity. The herd productivity is a complex trait that embodies several dimensions, such as growth, feed efficiency, reproduction, longevity and mortality. At farm level, it is important not only to have a fast growth, but also an efficient management increasing reproductive efficiency and reducing mortality and rate of unproductive animals.

Crosson et al. (2011) demonstrated that improvement of live weight gain is accompanied by a reduction of CFP. Hyland et al. (2016) well showed that farms that require more time to reach the slaughter weight also have a higher CFP, because they need more animals to have the same amount of meat produced, with a consequent increase of resource consumption and of emissions.

There are many factors that influence animal and environmental performances. White and Capper (2013) simulated an increase of 15% of the average daily gain in a typical feedlot in US and found that CFP decreased by 11.7%. In the same study they estimated that if finishing weight increases by 15% the corresponding effect on CFP was of 14.7%. The reason of the improvement is, as mentioned above, the dilution of maintenance requirements in the total animal's nutrient requirements (Capper, 2011).

There is no substantial difference between CFPs of beef produced in conventional and organic systems, because performances can be the same; however, the environmental burden referred to one hectare of cultivated area is much lower in organic than in conventional systems, with potential local consequences on water and air quality (Meier et al., 2015).

Breed and animal type are also important. As shown by Berton et al. (2016) the CFP of live weight gain of beef heifers during finishing period is significantly lower than those of bulls and, between bulls, Charolais and Irish cross are less impacting than French crosses or Limousin.

Animal welfare is considered conflicting with animal performances and some environmental categories. On the contrary there are many complementarities, because non-stressed and healthy animals are more productive and farm's environmental performances are better (Broom, 2019). From a practical perspective, it has been demonstrated that an appropriate herd management, by paying attention to animal welfare, animal health, and fertility, is one of the main strategies to reduce the environmental impact of livestock production (Hristov et al., 2013a; Williams et al., 2015). Van Soosten et al. (2020), reviewing a series of papers in dairy sector, concluded that poor animal welfare or diseases reduce dry matter intake and performances, determining an increase of emission intensity of GHG as well. In an ongoing research we have observed that installation of vertical fans, that reduce the temperature and the humidity inside stalls of beef cattle, improves animals' wellbeing, growth rates and CFP (data not published). The relationship between mitigation of global warming and animal welfare is bidirectional and is object of debate, because some mitigation strategies, such as improvement of productivity or feeding additives, are considered detrimental for animal welfare (Llonch et al, 2017; Shields and Orme-Evans, 2015). Anyway, contrast to global warming cannot be reduce the attention on animal condition.

Improvement of fertility and decreasing age at first calving are also strategies that can be adopted to improve whole productivity and environmental performances (Hristov et al., 2013b; Nguyen et al., 2012). Conversely, longevity is not considered determinant in decreasing CFP in beef farms (Beauchemin et al., 2011; Nguyen et al., 2012; Van Soosten et al. (2020). Although these traits and mortality are considered to influence the environmental sustainability of beef production, few LCA studies have been done in this regard.

-Genetic selection

Macleod et al. (2019) reviewed the strategies that can be followed to decrease enteric CH_4 emissions through genetic selection, beyond that possible by selecting for growth rate. The reduction of enteric CH_4 emissions is connected to feed efficiency, because feed intake is the main factor influencing enteric CH_4 production. Residual feed intake, which is used to express feed efficiency, is moderately heritable (0.26 to 0.43) but highly dependent on accurate measurement of individual animal feed intake (Basarab et al., 2013). Another way is

to select for animals that emit less enteric CH_4 independently to feed efficiency, because it has been observed that mammals influence the microbiota of the gut (Macleod et al., 2019).
From a herd perspective, Quinton et al. (2018) showed that genetic improvement efficiency traits can also reduce GHG emissions estimated in Irish beef cattle population. The improvement is driven by the effects on survival, maintenance feed requirements and calving interval and is much higher for emission intensity than for gross GHG emissions.

-Housing and manure management

Manure management starts in barn and continues in stocking areas. Strategies for reducing emissions of GHG are many with synergies and trades off (de Vries et al., 2015).
Manure are sources of CH_4 and N2O, but also of NH_4 and other gases that should also be considered for their effects on air and water quality. Several strategies can be adopted to reduce GHG emissions from the barn. Separation of urine and feces is useful, because urea volatilizes once it comes in contact with ureases present in feces, causing emissions of NH_3, CO_2 and N_2O (Hristov et al., 2011).
Straw-bedded system creates an aerobic environment favorable for N_2O emissions but not for CH_4. The opposite is with liquid-manure systems, that tend to increase CH_4 emissions and reduce those of N_2O and NH_3 (Chadwick et al., 2011; Hristov et al., 2013b; Montes et al., 2013). In the Italian report of national GHG, Cóndor et al. (2008) indicated an emission factor of 0.02 kg N-N_2O/kg of N excreted instead of 0.001 kg N-N_2O/kg of N excreted for dung and slurry respectively.
Petersen et al. (2013) summarized several experiments where the effects of covering manure facilities were tested; on the whole, covering manure with natural crust, straw, crop and wood residuals or semipermeable membranes is effective in reducing CH_4, while the effect N_2O emissions is controversial.
One of the factors influencing manure GHG emissions is the time they are stored: the shorter it is the less are the emissions of CH_4 and NH_3 (Hristov et al., 2013b).
Methane is produced in an anaerobic environment, for this reason regular removal of slurry prevents its formation. Amon et al. (2006) reported a reduction of 57% and an increase of 144% of emissions of CH_4 and N_2O respectively.
IPCC refinement (2019) also takes account of temperature in the barn and in the pits because methane conversion factor is sensitive to this parameter.
Manure acidification is an effective strategy that have been proposed for reducing NH_3 and CH_4 emissions (Petersen et al., 2012), but its effect on N_2O emissions is controversial too (Hristov et al., 2013b), but low pH results to reduce conversion of N_2O to N during conservation (IPCC, 2019).
Separation of manure between liquid and solid fraction is frequently adopted by farmers because facilitates handling and transport; even if some laboratory studies reported that separation cause an increase of GHG emissions from combined solid and liquid fractions (Dinuccio et al., 2011), it has been suggested that this strategy is effective in reducing CH_4 emission, even if it has been shown that this technique can increase NH_3 emissions (Holly et al., 2017) or both NH_3 and N_2O (Hristov et al., 2013b).
Kupper et al. (2020) have summarized results from farm-scale and pilot-scale studies and found that acidification showed a reduction of NH_3 and of CH_4 during storage and an increase of N_2O; solid-liquid separation caused higher losses for NH_3 and lower emissions for CH_4 and N_2O; digestate from AD had higher emissions of NH_3 and a reduction of those of CH_4, with minor changes for N_2O.
Although all the measures have listed above concerning manure management are well documented, it appears that there are a lot of factors that influence the results from their adoption. The results are inconsistent and in most cases application of these measures determine contrasting results for one gas and the other. It is interesting the meta-analysis performed byMohankumar Sajeev et al. (2018), which concluded that only frequent removal, anaerobic digestion, and manure acidification reduce NH_3, CH_4 and N_2O simultaneously and that other measures have contrasting effects on the three main gases.

-Manure application

The phase of agronomic distribution of manure is relevant of N-compounds emissions, while it is much less important for CH_4.
Manure contains organic C and available N. Manure C increases microbial respiration; this determines a reduction of oxygen availability creating an environment favorable for nitrification and synthesis of N_2O.

Nevertheless, use of manure can be a useful strategy to reduce CFP in beef production, because, as will be seen below, production of synthetic fertilizers increase N budget and their production requires large amounts of fossil fuels.
To reduce N losses and NH_4 and N_2O emissions, timing of manure application is of paramount importance. Trivially, avoiding manure application before an imminent rain is a good precaution for avoiding nutrient leaches and picks of emissions and several authors have reported that wet soils promote N_2O emissions (Hristov et al., 2013b).
Nitrogen losses occur immediately after the application and in 12 hours most of N is lost. However, these loses are strongly influenced by the application methods. The largest N losses occur with irrigation and broadcasting spreading, because of the NH_4 volatilization, but they are influenced by the time between application and plowing. Losses decrease with incorporation of surface manure; but direct incorporation of slurry into the soil is the method that reduces N loses the most (Rotz, 2004).
Saving N losses and reducing N_2O emissions as well is challenging, because emissions occur after manure application and increase with application methods that tend to reduce N losses (Rotz, 2004). Duncan et al. (2016) tested the effects of broadcast application versus shallow disk injection of dairy slurry on NH_3 volatilization and N_2O emissions and verified a reduction of 92-98% of the first one and an increase of 84-152% of the second ones. For this reason, it is crucial to apply the right amount of manure when plant is more active and requires more nutrients (Chadwick et al., 2011). Webb et al. (2014) studied the effect of immediate incorporation after distribution of four different types of manure on two different soils; they concluded that immediate incorporation reduces NH_4 emissions in both soils; but results on N_2O are contrasting and depending on incorporation technique and soil type.

-Inhibitors of nitrification and of ureases

Ureases is the enzyme that catalyses the reaction between urea and H_2O producing NH_3 and CO_2. The urease inhibitors stop this reaction and the production of NH_3 and, consequently, of N_2O. The most common inhibitor is N-(n-butyl) thriophosphorictriamide (nBTPT) that, to be effective, has to be applied before urine is mixed with feces or soil. For this reason, mBTPT can be utilized only on pastures (Montes et al., 2013). To overcome this limit, urea-based fertilizers are treated with mBTPT and emissions of NH_3, N_2O and NO_3 slow down.
Inhibitors of nitrification temporally suppress the activity of microorganisms converting NH_4^+ into NO_2, reducing the substrate for the formation of N_2O and NO_3 (Lam et al. 2017). Good results in reducing N_2O emissions from pastures have been obtained with Dicyandiamide (DCD), 3,4-dimethylpyrazole phosphate (DPPP) and Piramyrin (Di and Cameron, 2012; Krol et al., 2020; Misselbrook et al., 2014; Montes et al., 2013).

-Anaerobic digestion

Anaerobic digestion (AD) of manure from cattle reduce CFP of animal products in two ways. Primarily, animals produce biomasses that can be utilized for generating energy in competition with fossil fuel. Secondarily, AD removes CH_4 from manure, avoiding it being emitted to the atmosphere. In front of this advantage, NH_3 emissions from digestate are higher than from untreated manure (Fantin et al., 2015).In most cases manure is mixed with other animal or plant substrates, whose nature influence NH_3 and N_2O emissions from digestate and N availability on soil (Fouda et al., 2013).
Fusi et al. (2016) compared fife anaerobic plants fed different biomasses and found that plant fed only cow slurry produced 1 MWh of electricity, as functional unit, saving 395 kg of CO_2eq compared to that of Italian grid. This means that AD gives an "avoided product" that reduces carbon budget of the livestock farm.
Effect of AD on global warming potential has been extensively studied in dairy sector. Vida and Tedesco (2017) estimated a reduction of 24% of the CFP of 1 kg of fat and protein corrected milk; Battini et al. (2014) estimated that milk CFP decreases by 23.7% with the introduction of AD, but this reduction is of 36.5% when also digestate are digested again. This is possible because additional energy is produced and because quite all the residual potential CH_4 is extracted in the second digestion step.

-Vaccines and early stage programming

There are several innovative ideas to reduce enteric CH_4 emissions. Two of them have been discussed recently by Beauchemin et al. (2020) in a review: vaccination against methanogen microorganisms and programming early stage of life. The concept of the first strategy is based upon the hypothesis that a vaccine can induce immune system to produce antibodies that suppress methanogen growth. Results seem promising, but the extend of CH_4 reduction is not known so far and there is not information about productive performances and animal health. The hypothesis underpinning the second strategy is that microbioma can be oriented in the early state of ruminant life. First experiment has been done treating with bromochloromethane does and their kids. A reduction of CH_4 emissions was observed on both. No information is still available of long persistency of the effect.

Supplementary Material S5

References of Supplementary Materials

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Supplementary Figure S1

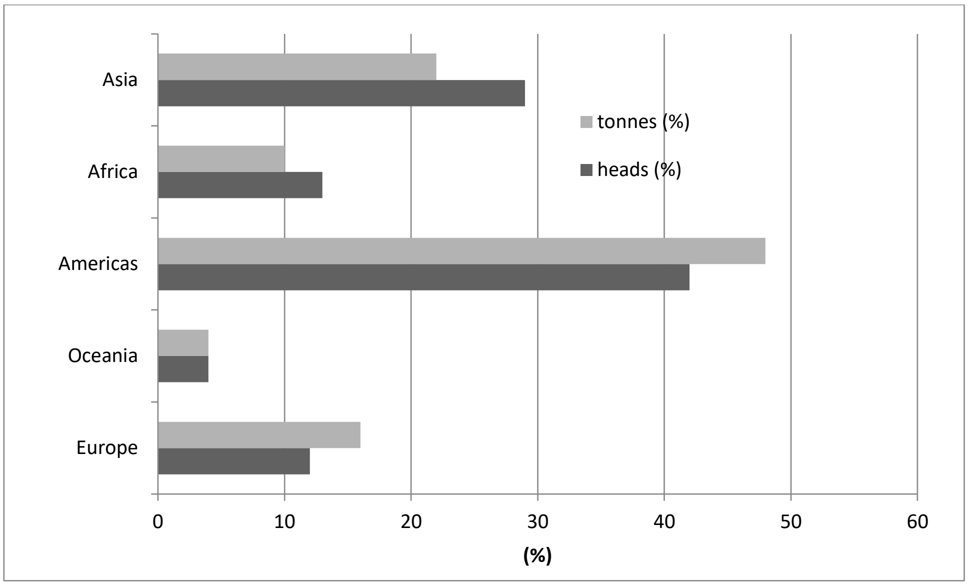

Figure 1 – Percentage incidence of the different continents on world’s cattle meat production as animal slaughtered (heads) and weigh of carcasses obtained (tonnes) (elaboration on FAOstat, 2020, data for year 2019)

Supplementary Figure S2

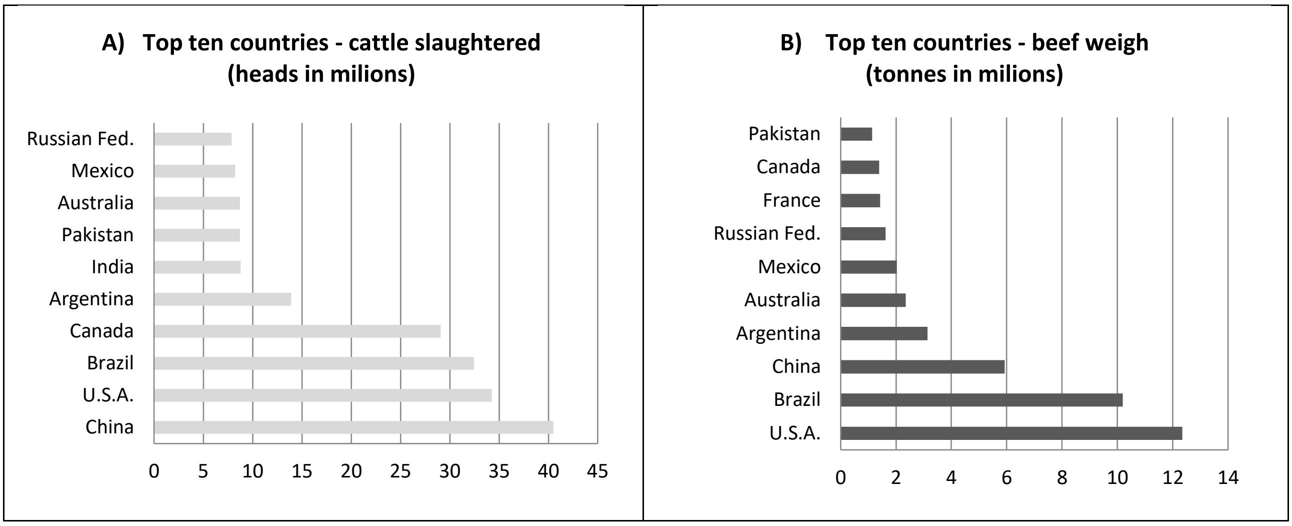

Figure 2 – Top ten beef producing countries by number of animals slaughtered (A) and tonnes of carcasses produced (B). Our elaboration on FAOstat, 2020, data for year 2019)