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Variation of greenhouse gas emissions and identification of their drivers during the fattening of Belgian Blue White bulls based on a LCA approach

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Abstract. Greenhouse gas emission intensity (GHGI; kilograms carbon dioxide equivalents/kilograms liveweight gain) have to be reduced so as to limit the impact of human activities on global warming while furnishing food to human. In this respect, performances of 654 Belgian Blue double-muscled bulls (BBdm) during their fattening phase were recorded. On this basis, their greenhouse gas emissions were modelled to estimate variation in GHGI and investigate mitigation options at that level. The relevance of theses option is discussed, taking into account the whole life and production system scales. Large variations (mean (s.d.)) were observed (from 7.2 (0.4) to 10.0 (0.7) kg carbon dioxide equivalents/kg liveweight gain) for, respectively, the 1st- and 4th-quantile groups defined for GHGI. Early culling, low liveweight and age at start of the fattening phase of the bulls would lead to a reduction of GHGI. Nevertheless, more than 32% of the variation remained unexplained. However, decision leading to reduction of GHG intensity at this stage of the life may be compensated in the early stage of BBdm. Attention is drawn on the necessity to encompass the whole life of BBdm for investigating mitigation options and on the sensitivity of the results on models and methodological choices.

Additional keywords: life-cycle assessment, mitigation, system approach.

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Introduction

Production of enough food, under environment-friendly ways, represents a major challenge for worldwide agricultural systems. Indeed, major adaptations of these systems are expected to answer to the evolution of human nutritional behaviour and populations, leading to an increase in meat requirement (Alexandratos and Bruinsma 2012). However meat, especially when originating from ruminant, is strongly criticised for its impact on (1) the environment (climate change, eutrophication, . . .; Steinfeld *et al.* 2006) and (2) resource consumption, compared with plant-based diet (Nijdam *et al.* 2012; van Dooren *et al.* 2014). Even in a context of constant production, reduction of greenhouse gas (GHG) emission intensity (i.e. kg GHG/kg of product, GHGI) for ruminant-based products is possible and desirable by the implementation of mitigation measures related to feed production and animal nutrition, animal genetics and breeding, rumen micro-biome modification, animal health, manure management and grassland management (GRA 2015). Belgian Blue double-muscled bulls (BBdm) breed is well known for its high diet-density requirements and efficiency in converting feed to fat-poor meat (De Campeneere *et al.* 2001). The production of those animals is typically based on a rearing phase followed by a fattening phase based on rich diets (Fiems *et al.* 2002). Those phases are most of the time performed in different specialised farms. At beef production-system level, it has been shown that the suckler-calf section of the system highly contributes to GHG emissions (Nguyen *et al.* 2012). Considering only the bull life, the fattening phase contributes to ~35% (e.g. Pelletier *et al.* 2010; Koch and Salou 2013) of the GHG emissions and is partially a function of the hypotheses (allocation between co-products) used (Doreau *et al.* 2011). However, large individual variations in performances and GHGI are expected (Basarab *et al.* 2013) and referential values for benchmarking GHG emissions and mitigation opportunities related to cattle-based products are required. In this respect, the fattening phase is the most controlled and well known phase of life in terms of performances (feed intake and cattle performance measurements) of the BBdm. Therefore, quantification of variation in performances, GHGI and identification of their drivers at this stage of the BBdm life could be considered as a first step to reduce GHGI on the whole life of the BBdm. Such approach could guide the production sector through improvement. However, due to the complexity of agricultural systems (de Boer *et al.* 2011), other life stages of the BBdm have to be considered to avoid negative interaction on GHGI. In the present study, GHG emissions of BBdm bulls were assessed at fattening phase on the basis of data from a commercial fattening BBdm farm, with individual bull performances recorded. This was done through an attributional (Finnveden *et al.* 2009) life-cycle assessment (LCA) approach. The purpose of this approach was not to define absolute value of GHGI for BBdm, but the identification of explaining drivers for the variation of these emissions, and to discuss them in the perspective of the whole life of the animals and the production system levels.

Materials and methods

Goal and scope

The purpose of the present study was to investigate variations and best practices to reduce GHGI, i.e. greenhouse gas (GHG)/kg of liveweight gain (LWG), of BBdm production during the fattening phase. It was based on the modelling of GHG emissions (carbon dioxide equivalent (CO_{2eq}.) on 100-year time frame; IPCC 2007) during bull fattening phase and, on the identification of drivers explaining the variability observed, including some related to the whole life of those animals. We focussed on the bull life and did not include suckler-cow production system. However, GHGI and mitigation options were discussed according to different points of view in the BBdm production system, representing (1) the most focussed one, namely, the ‘fattener’ point of view, where the target was to identify drivers for improvement, (2) the ‘rearer-fattener’ point of view, which is involved from birth to the slaughter and may influence a larger part of the bull life, and (3) the ‘citizen’ point of view, which represents the most systemic approach, including, at least, the emissions related to the pregnancy of the suckler cow as considered in the attributional approach implemented by LCA practitioner (FAO 2015). This research involved 654 Belgian Blue bulls fattened between August 2012 and August 2015 in a commercial barn located at Ath (Belgium, 50°36′37″N, 3°46′15″E, altitude: 57 asl). As currently undertaken to fatten BBdm (De Campeneere *et al.* 1999; Fiems *et al.* 2002), a double-feeding phase procedure was applied, including growing and finishing phases. During the growing phase (140 (30) days, Table 1), the bulls received a diet with a lower energy concentration than during finishing phase (140 (40) days). The growing phase was kept relatively constant in duration, while the finishing phase was adjusted to enable animals to reach similar liveweights at culling (673 (58) kg). TheBBdm diets were mainly based on concentrate (Table 1, ~92% of the diet on a DM basis). In parallel, bulls had free access to spelt straw (feed area and litter). Straw intake was estimated to cover 8% of the diet, on a DM basis, according to requirement for feed structure (ADLO 2013). Total diet energy digestibility (dE: kJ/kJ) and crude protein concentrations were of 0.698 and 0.708 kJ/kJ and 178 and 170 g/kg DM during the growing and finishing phases, respectively. Bulls were weighed at least at the start and at the end of each phase.

Table 1. Diet composition (straw excluded) proposed to bulls during the fattening phases

Neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL), the fibre fractions (derived from Van Soest *et al.* 1991); DVE, digestible feed and microbial true protein in the small intestine; VEVI, net energy for fattening; OEB, degraded protein balance (nutritive value of forage following the Dutch system; Van Vliet 1997; and Tamminga *et al.* 1994); dE, gross energy digestibility

Parameter	Unit	Growing	Finishing
Item			
Product derived from beet pulp	g/kg DM	343	325
cereals	g/kg DM	116	208
Products derived from cereals	g/kg DM	267	171
Protein feed	g/kg DM	143	98
Soybean	g/kg DM	21	61
Oil plant seeds	g/kg DM	8	46
Cellulosic products from oil plant seeds	g/kg DM	82	64
Vegetal oil	g/kg DM	3	4
Mineral	g/kg DM	17	22
Characteristic			
DM	g/kg FM	886	886
Crude protein	g/kg DM	191	182
Ash	g/kg DM	81	77
ADF	g/kg DM	177	170
NDF	g/kg DM	363	307
ADL	g/kg DM	28.2	27.0
DVE	/kg DM	129	131
OEB	/kg DM	–0.453	0.490
VEVI	/kg DM	1198	1245
dE	kJ/kJ	0.72	0.73

Inventory

Bull liveweights (LW) were measured at least three times, including (1) at their arrival, (2) after the growing phase and (3) after the finishing phase, so as to record LWG and daily LWG (DLWG). They were culled and their carcass production was measured (carcass weight, CW), together with their CW to LW ratio (CW : LW ratio) at slaughter house. BBdm were kept in pens of six to eight bulls on deep litter system. During their fattening phase, concentrate consumption was weighted daily individually, using automatic concentrate distributor, to estimate the feed conversion ratio (FCR: dry matter intake (DMI)/LWG). Water, electricity, straw for litter, diesel and lubricant for farm operation were recorded at a building level and calculated individually, as summarised in Table 2. Buildings used were also calculated at an animal level. GHG emissions from inputs (Table 2, Fig. 1) came from Koch and Salou (2013) (version 1.1), Nemecek and Kägi (2007) (version 3.1) and regional LCA for cereal production (F. Van Stappen, M. Mathot, A. Loriers, A. Delcour, D. Stilmant, B. Bodson, V. Planchon and J.-P. Goffart, unpubl. data).

Greenhouse gas emissions during the fattening phase were estimated for each animal. They included the emissions related to (1) inputs, as previously mentioned, (2) the direct emission by the animals and (3) the direct and indirect emissions from the manure produced up to the end of their storage period (Fig. 1). The manure produced was considered as residue, i.e. it was not a co-product

Table 2. Input consumption and emission factors (EF)
$CO_{2eq.}$, carbon dioxide equivalent

Parameter	Consumption	Unit	EF ($CO_{2eq.}$)	Unit
Straw (litter and feed)	4.16	kg DM/head/day	0.127	kg/kg DM
Water	21.5	kg/head/day	0.275	kg/m^3
Buildings	2	m^2/100 kg LW	4.07	kg/m^2/y
Diesel	0.015	kg/head/day	3.07	kg/kg
Machinery	0.0035	h/head/day	7.72	kg/h
Electricity	0.1457	Kwh/head/day	0.085	kg/kwh
Concentrate growing phase	Table 3		0.690	kg/kg DM
Concentrate finishing phase	Table 3		0.670	kg/kg DM

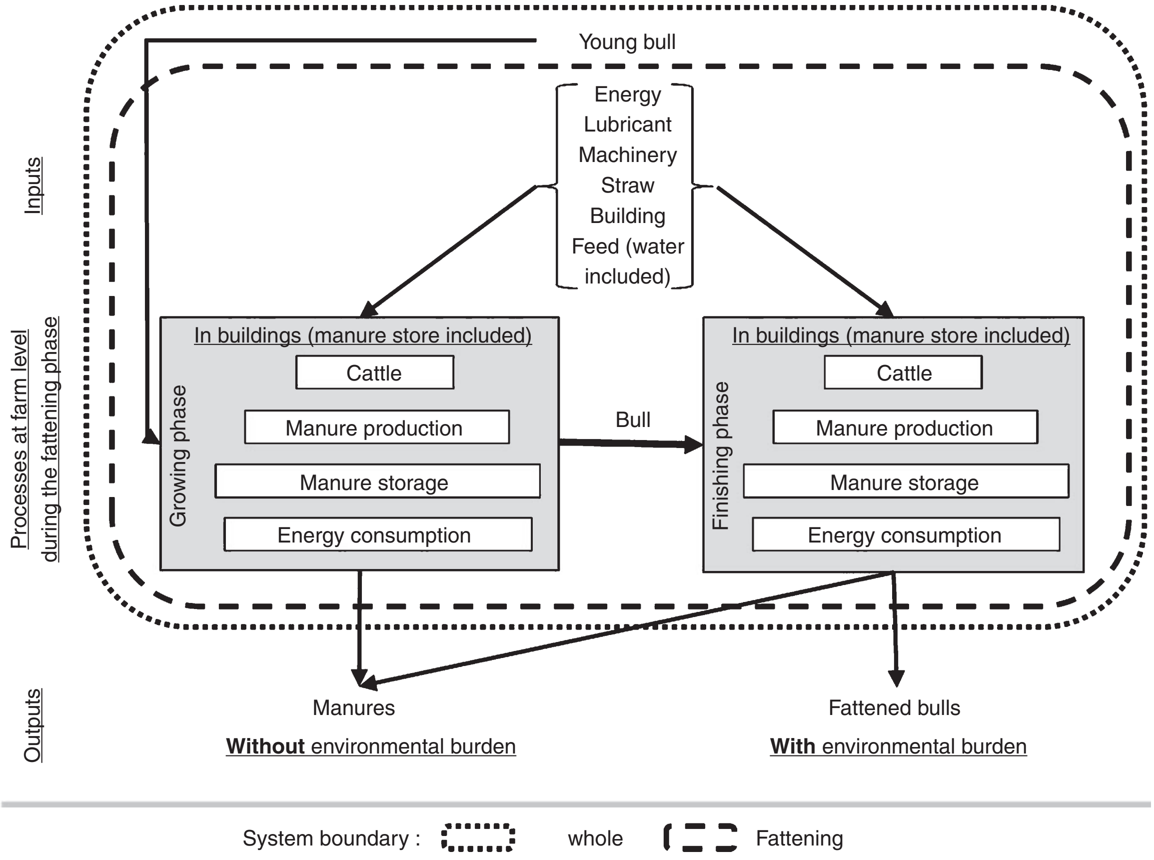

Fig. 1. Systems description and boundary.

or a waste. Models, hypotheses and secondary data used are summarised in Tables 2 and 3. Methane emissions by cattle were based on IPCC (2006) but, in the present research, the proportion of the energy lost as methane and, thus, emitted was considered to decrease with feed digestibility according to Gerber *et al.* (2013). The amount of gross energy ingested was calculated at an animal level using feed intake recorded on an individual basis. Direct emissions of CH_4 and N_2O by manure were estimated with IPCC (2006) model, using deep bedding emission factor for beef cattle and a measured parameter (DMI, LWG, feed composition) for nitrogen and organic matter excretion. The NH_3, NO and NO_3^- emissions from manure, in barn and during storage, leading to indirect emission of N_2O, were estimated with EMEP (2013) and IPCC (2006), using the emission factor from solid manure of beef cattle in barn and store. Emissions from manure after their storage were not attributed to the animals.

Herd description

At the beginning of the fattening phase, the 654 bulls were, on average (s.d.), of 300 (53) kg LW and 314 (64) days old. Considering the LW of 45 kg at birth, their LWGs were, on average, of 823 (156) g/day during the rearing phase. The bulls originated from 68 different bull-rearing farms. Among the 654 bulls, 308 originated from eight farms that furnished at least

Table 3. Models, hypotheses and references used

$CO_{2eq.}$, carbon dioxide equivalent

Item	Equation	References and comments
	Direct emissions from beef and manure	
Enteric CH_4	(9.75–0.05 × energy digestibility)/100 × (ingestion (kg DM)/18,45)/55,65	Gerber *et al*. (2013) and IPCC (2006). The gross energy digestibility is considered as identical for all animals for a given diet. The proportion of energy lost as CH_4 of the total gross energy ingested decrease with the digestibility of the ration.
N_2O from solid manure storage	EF_N_2O × amount of N excreted (kg N)	IPCC 2006. N excretion is calculated using the ingested minus the N retained in animal gains estimated from LWG.
CH_4 from manure stored	EF_CH_4Store × VS excreted (kg DM)	IPCC (2006), the amount of volatile solid (VS) excreted is calculated thanks to the gross energy digestibility and gross energy concentration of the ration and the amount of feed ingested. dE is considered as equal for all animals for a given diet
NH_3 from manure at barn and storage facilities	EF_NH_3b × TAN excreted (kg N)	EMEP (2013) TAN is calculated using N excreted multiplied by default ratio TAN/total N excreted
NO_3, NH_3 and NO from manure at storage facilities leading to indirect N_2O emissions	EF_NH_3s × TAN stored (kg N)	EMEP (2013) and IPCC (2006)
	Indirect emissions and direct emissions from energy consumption	
Feed	EF_Feed (kg $CO_{2eq.}$/kg DMI) × dry matter intake (DMI)	Based on Nemecek and Kägi (2007). Variation in soil carbon amount excluded.
Straw (litter)	EF_straw (kg CO_2eq./DM) × amount used ratio (DM/kg VS excreted) × amount of VS excreted	Amount used proportion estimated from (Mathot *et al.* 2013). VS calculated following IPCC (2006). EF based on F. Van Stappen, M. Mathot, A. Loriers, A. Delcour, D. Stilmant, B. Bodson, V. Planchon and J.-P. Goffart (unpubl. data). Variation in soil carbon amount excluded.
Water	EF_Water (kg $CO_{2eq.}$/litre) × average measured amount used (L) × proportional factor for DMI	Water is supposed to be directly correlated with feed intake
Buildings	EF_build (kg $CO_{2eq.}/m^2$.day.100 kg de LW) × amount (average LW × duration (days))	Amount of building use dis proportional to the cattle size and duration of the fattening phase. The EF is derived from Koch and Salou (2013)
Gazoil	EF_gasoil (kg $CO_{2eq.}$/kg) × amount used (kg) × proportional factor for DMI	Amount of gasoil consumed is considered to be proportional to the DMI because most of the gasoil is used by cattle feeding operation[A]
Electricity	EF_electricity (kg $CO_{2eq.}$/kwh)) × average amount used (kwh) × proportional factor for DMI	Idem gasoil
Machinery	EF_machinery (kg $CO_{2eq.}$/kg) × average amount used (kg) × proportional factor for DMI	Idem gasoil

[A] Individual DMI/total DMI.

20 bulls. This smaller population was considered to investigate parameters influencing GHGI, including the origin of the bulls.

Statistical analyses

The population was sorted in four equal-sized groups according to the ranking (quantiles 0–25 (p25), 25–50 (p50), 50–75 (p75) and 75–100 (p100)) for GHGI during the whole fattening phase. The groups were compared for animal characteristics and performances using non-parametrical statistical procedures (Kruskal–Wallis and Nemeny tests) with the statistical software R Core Team 2014), to account for distortion in conditions (mainly normality) for parametric-test application, due to procedure of group formation on the basis of quantiles. The results provided by this procedure were completed by first-order regression after stepwise approach ('Step' procedure with both direction option, R Core Team 2014) for identification of GHGI ($CO_{2eq.}$ per kg LWG) drivers related to the rearing phase of the bulls (initial age and weight at the start of the fattening phase, DLWG during rearing and origins), the culling age and fattening phase duration. If not otherwise specified, results are presented as means (standard deviation).

Results

Group approach (Table 4)

The GHGIs during the fattening phase were estimated at 8.5 (1.1) kg $CO_{2eq.}$/kg LWG for a FCR of 5.6 (0.8) kg DMI/kg LWG. The average DLWG was 1350 (179) g/day. The bulls were culled at 673 (58) kg at the age of 594 (57) days.

Greenhouse gas emissions were due, in a decreasing order, to feed production (41.1 (0.1)%), to methane emissions from the

Table 4. Main emissions (kg carbon dioxide equivalent (CO_2eq.)/kg liveweigt gain (LWG)), and whole-population and quantile-group characteristics
For a given variable, groups with different letters are significantly different (at $P = 0.05$, Kruskal–Wallis and Nemeny tests)

Variable	All animals	Emission groups during fattening phase (percentiles of kg CO_2eq./kg LWG)			
	0–100%	p25: 0–25%[A]	p50: 25–50%	p75: 50–75%	p100: 75–100%
		GHG emissions (*kg CO_2eq./kg LWG*)			
Fattening	8.5 (1.1)	7.2 (0.4)a	8.0 (0.2)b	8.7 (0.2)c	10.0 (0.7)d
		FCR (*kg DM/kg LWG*)			
Growing	4.7 (0.7)	4.1 (0.5)a	4.4 (0.5)b	4.7 0.5)c	5.4 (0.7)d
Finishing	6.8 (1.3)	5.5 (0.7)a	6.4 (0.9)b	7.0 (1.0)c	8.3 (1.5)d
Fattening[B]	5.6 (0.8)	4.7 (0.3)a	5.3 (0.1)b	5.7 (0.2)c	6.6 (0.5)d
		Age (days)			
Growing (start)	314 (64)	311 (70)a	303 (63)a	313 (58)a	332 (64)b
Finishing (start)	454 (62)	445 (65)a	444 (57)a	456 (56)a	472 (65)b
Cull	594 (57)	571 (54)a	585 (52)b	602 (51)c	619 (60)c
		Period duration (*days*)			
Growing	140 (30)	134 (26)a	141 (33)a	142 (32)a	140 (29)a
Finishing	140 (40)	126 (37)a	141 (35)b	146 (31)b	147 (48)b
Fattening	279 (52)	260 (48)a	282 (49)b	288 (49)b	287 (57)b
		LW (kg)			
Growing (start)	300 (53)	287 (50)a	281 (52)a	298 (47)b	332 (51)c
Finishing (start)	498 (60)	495 (57)a	485 (62)a	497 (54)a	516 (65)b
Cull weight	673 (58)	683 (56)a	670 (55)a	671 (56)a	669 (65)a
		DLWG (*g LWG/day*)			
Rearing	823 (156)	798 (155)a	793 (156)a	820 (150)a	881 (148)b
Growing	1418 (209)	1548 (205)a	1436 (191)b	1390 (165)b	1297 (190)c
Finishing	1277 (283)	1522 (256)a	1324 (219)b	1207 (198)c	1056 (229)d
Fattening	1350 (179)	1537 (151)a	1386 (109)b	1298 (97)c	1175 (117)d
Life	1064 (123)	1126 (132)a	1075 (114)b	1045 (107)bc	1013 (109)c
		Carcass yield (*g/kg LW*)			
Life	698 (14)	697 (13)a	698 (15)a	698 (14)a	699 (12)a

[A] The groups are defined by the quantile determination on the greenhouse gas emission intensity on the whole fattening phase of the Belgian Blue double-muscled bulls (BBdm).

[B] On a DM basis of total diet (straw included).

animals (33.8 (0.1)%), to the emissions from the manure (CH_4 and N_2O; respectively 10.1 (<0.1)% and 6.3 (<0.1)%), to the emission for straw production (4.7 (<0.1)%), to the indirect N_2O emissions (2.1 (0.1)%) and to the other factors (buildings, diesel, machinery, electricity and water) for ~2 (0.1)%. This distribution lead to a strong relationship between FCR and GHGI ($r^2 = 0.999$, GHG/LWG = –0.187 + 1.55 × FC) due to proportional impact of feed production on direct emissions by bulls and their manure. Input emission factors and average consumption are reported in Table 4.

Distribution in groups according to the bull ranking on GHGI led to the observation that there were significant variations in (1) the BBdm initial age at the beginning of the growing phase, with older animals in the p100 group, (2) the age at the beginning of the finishing phase, with older animals in the p100 group and (3) the age of culling that is correlated with GHGI emission ranking. Duration of the growing phase was similar for all groups, whereas the duration of the finishing phase increased with the emission rate groups (from p25 to p100). There were no differences in animal LW at slaughter or in CW : LW ratio, with a total average value of 0.698 (0.013). On average, the DLWG decreased with the GHGI. Globally, these observations showed that animals of the most emitting group (p100) were bigger at the beginning of the fattening period and older than the others and that they had a lower DLWG during the fattening phase but a higher DLWG during the rearing phase. The lowest-emitting animal group (p25) differed from the intermediate groups (p50 and p75), mainly by a higher DLWG during the whole fattening phase.

Regression approach

This analysis was performed on 308 bulls according to the selection criteria of their origin (more than 20 BBdm by rearing farm). Each of the remaining BBdm rearing farms provided from 22 to 88 bulls. GHGI was mainly explained ($r^2 = 0.677$, adjusted $r^2 = 0.539$), in a decreasing order, by culling age (32% of the variation), LW at the beginning of the fattening phase (12%), BBdm origin (11%) and initial age (2%) at the beginning of the fattening phase. No interaction between these variables influenced GHGI significantly. More specifically, GHGI was positively influenced by the initial LW (9.4×10^{-3} kg $CO_{2eq.}$/(kg LWG × kg LW)), culling age (16.2×10^{-3} kg $CO_{2eq.}$/(kg LW × days)), while it was negatively influenced by the initial age (-8.4×10^{-3} kg $CO_{2eq.}$/(kg LW × days)). It should be noted that DLWG during the rearing phase was not retained as the main explaining variable. The average emission intensity varied significantly ($P < 0.05$), from 7.8 (1.0) to 9.3 (1.2) kg $CO_{2eq.}$/LWG with the origin of the bulls.

Discussion

On the whole fattening period of the BBdm, their GHGI and FCR, which were highly correlated, varied strongly (reduction of 30% from p100 to p25). According to the quantile-group approach, the following two main groups of BBdm can be distinguished: the bulls that start to be fattened early, with a low liveweight (from percentile 0 to 75), and those that start to be fattened lately, and with a higher liveweight due also to a higher DLWG during the rearing phase (p100). This second group showed, on average, lower zootechnical performances all along the fattening phase and the bulls were older at culling. Among the first groups (p25–p75), the most efficient animals (p25) showed constant and high performances during the whole fattening phase (DLWG = ~1.5 kg/day), while, with increasing percentile (groups p50 and p75), the performances decreased and the differences increased at the finishing phase, compared with the growing phase. These trends were confirmed with the regression approach that also highlighted the impact of the origin of the animals. The positive relation between emission intensity and the age at culling can be explained by the decrease of the requirement for growth to maintenance ratio with increasing cattle age and, thus, LW (e.g. IPCC 2006), notably due to losing the potential for growing (ADLO 2013). The positive but weak relationship of emission intensity with the initial LW at the fattening phase can be explained by compensatory growth during the fattening phase for the lightest animals (Fiems *et al.* 2002). The negative relationship with the initial fattening age can be explained by the longer duration of the fattening period where high growth potential of the BBdm was expected partly due to rich diet. However, ~32% of the variation in GHGI was not explained, while 11% was explained by the BBdm origin. It cannot be determined whether the last 11% was due to genetic factors or to the management of the cattle during the rearing phase. Also, part of the 32% of variation not explained can be due to genetic factors and management, but it was not possible to test these explaining variables properly. The variation among groups and the relationhips with explaining variables indicated that improvement in efficiency is probably possible during the whole fattening phase, partially by selection of animals that have high and relatively constant performances during the whole fattening phase, but also by adapted management practices such as avoiding culling too old bulls or selecting young and light BBdm for the fattening phase. For the first option, measurable parameters at the beginning of the fattening indicating potential high performances during this phase have to be identified.

According to the models used, the digestibility and methane emission rates of the diets (~ 20 g CH_4/kg DMI) were considered as identical for all bulls. The total ammoniacal nitrogen (TAN) to total nitrogen ratio in excretion was also considered as constant. However, these hypothesis have to be confirmed (Basarab *et al.* 2013) because variation in the organic matter digestibility of feed and the excretion concentration in nitrogen compounds may also influence gas emissions from manure. Similar GHGI (from 7.8 to 12 kg $CO_{2eq.}$/kg LWG) for Charolais bulls in finishing phase were derived from Koch and Salou (2013), as implemented in Simapro® software (Pré 2013). According to their methodology, the fattening phase contributes only ~33% of the total emissions over the whole life of the bull, but ~50% of the LWG. Therefore, GHGI over the whole life has to be considered, so as to investigate the potential impact of bull meat production. Therefore, the relationship between GHGI during the fattening phase and the GHGI during the rearing phase has to be analysed to choose mitigation options. In other words, it has to be investigated whether decision to reduce emission intensity at the fattening phase according to the identified drivers may or may not be compensated by emissions during the rearing phase. This last phase is, to our knowledge, by far less well known for BBdm.

Except culling age, major drivers influencing the GHGI of the fattening phase can typically be modulated by the rearing phase. However, this induces a large uncertainty on potential decision to reduce GHGI at the whole product scale. Indeed, for example, high LW and age at the beginning of the fattening phase can be reduced by starting the fattening earlier. But, we have no indication of the GHGI of the rearing phase. If this GHGI is lower during the rearing phase, then the effects of an earlier start of the fattening phase would be an increase of the GHGI over the whole life of the bull. Indeed, lower GHGI during early life of the bull can be expected, considering that grass-based products are dominant in its diet, and when carbon sequestration in grassland soil is included (Pelletier *et al.* 2010). However, the rate of carbon sequestration in soils is highly variable (Soussana and Lemaire 2014) and the ability of grassland to perpetually store carbon in soil is still debated (Smith 2014). Whether carbon sequestration in soils is accounted for or not is, therefore, probably a critical factor in finding mitigation options for to BBdm management.

For a given animal, according our results, a mitigation option could be to modify the life time to reach optimum culling age for minimum GHGI. However, this option would require a regular recording of individual performances (feed intake, growth) at a level on an individual animal, and, thus, a high level of technicality and material in the fattening farm, and even more so with wet-feed diets. Furthermore, beside practical feasibility at the farm level, optimum culling age or size approach will induce variation in meat quality (e.g. fat content) and animal size, which may constrain potential valorisation in the transformation sector.

To emphasise the difficulties in finding mitigation options at the fattening phase, a conceptual approach is presented in Fig. 2. The graphs are based on a relationship between feed ingestion and animal LW as modelled from (1) data (feed ingestion and liveweight) from the present work, (2) data (feed ingestion and liveweight) concerning bulls before weaning and (3) bull maximum LW. It illustrates how optimising culling LW of a given bull for low GHGI during fattening phase does not necessary imply minimum GHGI over the whole life of the bull. Indeed, the evaluation of the GHG emissions ('Citizen' point of view, Fig. 2) of bull meat production requires accounting for the 'before birth' phase, i.e. at least the emissions due to pregnancy and lactation of the cattle before weaning, as recommended in LCA approaches (Koch and Salou 2013; Thoma *et al.* 2013). Optimum culling LW for the fattening phase ('Fattener' point of view, Fig. 1) seems to be lighter than for optimum GHGI from ('citizen' point of view, Fig. 2) or 'rearer-fattener' point of view that excludes the 'before

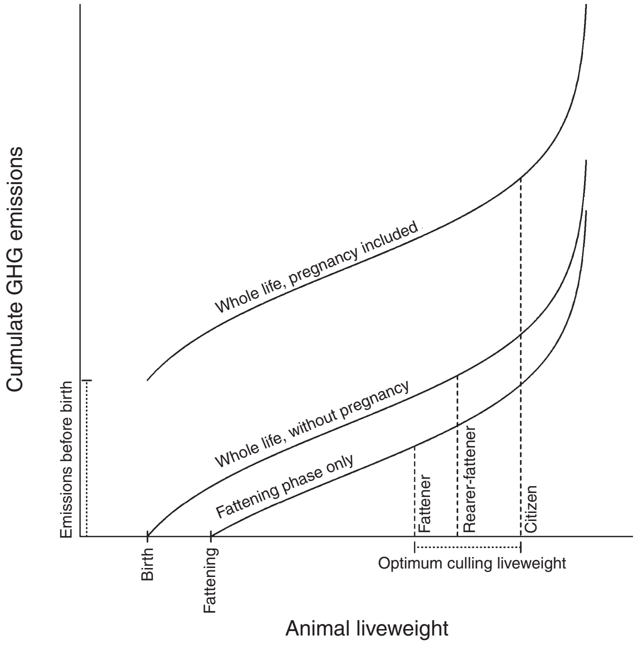

Fig. 2. Theoretical approach of the variation in optimal animal culling liveweight according to total ('citizen'), 'rearer-fattener' and 'fattener' point of view. Emissions before birth simulate the part of the mother's greenhouse gas emissions attributed to the pregnancy.

birth' emissions, but takes into account the emissions during the rearing phase. All these additional emissions have to be diluted in the LWG during the fattening period. As an example, according to similar curve shape (left = 0 kg and right = 1300 kg asymptote), birthweight of 48 kg (Herdbook 2015) and adult liveweight of 1300 kg, data from Koch and Salou (2013) lead to optimum fattening cull LW of 1081, 973 and 917 kg and GHG of 15.4, 11.9 and 11 kg CO_2eq./kg LW produced for 'citizen', 'rearer-fattener' and 'fattener' point of views, respectively. Culling the bulls at 917 kg would lead to an increase of ~3% of the GHG intensity, considering the 'citizen' point of view.

However, those differences depend at least on (1) the form of the curve linking cumulative GHG emissions to animal LW that must be precise and (2) the inclusion of emissions related to the period preceding birth (pregnancy and before), which remains a subject of methodological debate (e.g. FAO 2015), and (3) the inclusion or not of carbon sequestration in grassland soil and/or to land-use change, which may modify the results significantly (Nguyen *et al*. 2012). Indeed, grass is potentially the major source of feed in the before-fattening life period of the BBdm (ADLO 2013) and of its mother. This could lead to modification of the difference between 'fattener' and 'citizen' point of views. Furthermore, allocation of impact relative to some part of the suckler-cow life to BBdm implies modification of the GHGI of other co-products of the whole beef production system, at least of the culled cow. Finally, the choice of considering manure production as a residue may also influence the results. It could have been considered not as a residue, but as a co-product, and then have an environmental load of, and in consequence, reduction in GHGI of the BBdm. As an example, according to system expansion (Finnveden *et al*. 2009) and considering the emission of GHG from mineral fertilisers (Nemecek and Kägi 2007; Version 3.1) as an alternative in a 1 to 1 ratio with N, P K in manure, calculated for N and derived from AGW (2011), for P and K, average emissions would have been reduced to 7.7 (1.2) CO_2eq./kg LW produced. However, this leads to a minor change in the ranking of the animal due to an increase in N excretion with FCR (GHGI (with system extension for manure production) = 1.006 × GHGI-0.799). These observations emphasise the difficulties of finding a management practice, at one-actor level (here the fattener), leading to mitigation of GHGI over the whole life of the product in a multi actor and multi-product system, such as BBdm in the beef production sector.

Thus, ideally, from an environmental point of view, due to the drivers leading to variation in GHGI during the fattening phase, the potential trade-off with the rearing phase and the impact way of the 'before birth' emissions is accounted for, GHGI should be estimated, at least, considering the complete individual animal lifetime, and the consequence of these methodological choices should be taken into account. One option would be to individually adjust culling age to the minimum GHGI. However, this would require methodological choices and, modelling, as precisely as possible, the relationship between the cumulative GHG emissions and animal LW.

Conclusions

The large variation in the modelled GHGI during the fattening phase of BBdm bulls suggested potential mitigations options during this phase. Indeed, this variation is related to animal efficiency, as estimated through FCR, with, at this live stage, a lower impact for the most efficient animals. Nevertheless, it is also partially explained by the early life of the animal and its characteristics at the beginning of the fattening phase. Therefore, investigations have to be conducted to determine the relationship between before fattening life of the bull and its performance during their fattening phase. This would allow to (1) identify mitigations options and (2) determine whether and how low GHGI during the fattening phase is related to low GHGI over the whole life of the BBdm. However, in the present study, more than 33% of the GHGI variation during the fattening phase remained unexplained. Genetic factors could be one driver explaining, at least, some of the residual, unexplained variability and be a mitigation option. As underlined in the discussion, potential improvement, through management, to reach minimum GHGI have to be considered regarding the whole life of the BBdm and the whole production system. In this respect, further research on GHG emissions at animal and plant production (e.g. grassland soil carbon sequestration) levels and agreement about accounting methodology are required.

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References

ADLO (2013) 'Voeding van runderen van het belgisch witblauw ras.' (Vlaams Overhied Departement Landbouw an Visserij, Afdeling Duurzame Landbouwintwikkeling Voorlichting en Vorming: Brussels, Belgium) [In Dutch] Available at http://lv.vlaanderen.be/nl/voorlichting-info/publicaties [Verified 15 December 2015]

AGW (2011) Arrêté du gouvernement wallon modifiant le livre II du code de l'environnement contenant le code de l'eau en ce qui concerne la gestion durable de l'azote en agriculture, 31 March 2011. Available at http://www.ejustice.just.fgov.be [Verified 15 December 2015]

Alexandratos N, Bruinsma J (2012) 'World agriculture towards 2030/2050: the 2012 revision.' ESA working paper No. 12-03. (FAO: Rome)

Basarab JA, Beauchemin KA, Baron VS, Ominski KH, Guan LL, Miller SP, Crowley JJ (2013) Reducing GHG emissions through genetic improvement for feed efficiency: effects on economically important traits and enteric methane production. *Animal* **7**, 303–315. doi:10.1017/S1751731113000888

de Boer I, Cederberg C, Eady S, Gollnow S, Kristensen T, Macleod M, Meul M, Nemecek T, Phong L, Thoma G, van der Werf H, Williams A, Zonderland-Thomassen M (2011) Greenhouse gas mitigation in animal production: towards an integrated life cycle sustainability assessment. *Current Opinion in Environmental Sustainability* **3**, 423–431. doi:10.1016/j.cosust.2011.08.007

De Campeneere S, Fiems LO, Cottyn BG, Boucqué CV (1999) Phase-feeding to optimize performance and quality of Belgian Blue double-muscled bulls. *Animal Science* **69**, 275–285.

De Campeneere S, Fiems LO, Boucqué ChV (2001) Energy and protein requirements of Belgian Blue double-muscled bulls. *Animal Feed Science and Technology* **90**, 153–167. doi:10.1016/S0377-8401(01)00217-6

Doreau M, van der Werf HMG, Micol D, Dubroeucq H, Agabriel J, Rochette Y, Martin C (2011) Enteric methane production and greenhouse gases balance of diets differing in concentrate in the fattening phase of a beef production system. *Journal of Animal Science* **89**, 2518–2528. doi:10.2527/jas.2010-3140

EMEP (2013) 'Air pollutant emission inventory guidebook. Part B: sectoral guidance chapters. Chapter 3.B: Agriculture – Manure management.' Available at http://www.eea.europa.eu/publications/emep-eea-guidebook-2013 [Verified 15 December 2015]

FAO (2015) Environmental Performance of Large Ruminant Supply Chains: Guidelines for quantification, Rome, Italy. Available at http://www.fao.org/partnerships/leap/resources/public-review/en/ [Verified 15 December 2015]

Fiems LO, De Campeneere S, De Boever JL, Vanacker JM (2002) Performance of double-muscled bulls affected by grazing or restricted indoor feed intake during the growing period followed by finishing up to two different slaughter weights. *Livestock Production Science* **77**, 35–43. doi:10.1016/S0301-6226(02)00027-1

Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in life cycle assessment. *Jounral of. Environmental. Management* **91**, 1–21. doi:10.1016/j.jenvman.2009.06.018

Gerber P, Opio C, Food and Agriculture Organization of the United Nations, Animal Production and Health Division (2013) Greenhouse gas emission from ruminant supply chains: a global life cycle assessment. Rome, Italy.

GRA (2015) 'Reducing greenhouse gas emissions from livestock: best practice and emerging options.' Available at http://globalresearchalliance.org [Verified August 2015]

Herdbook (2015) Les performances de la race Charolaise. Available at http://www.charolaise.fr/Chiffres-cles [Verified 15 December 2015]

IPCC (2006) 2006 IPCC guidelines for national greenhouse gas inventories. In 'IPCC national greenhouse gas inventories programme'. (Eds LB Simon Eggleston, K Miwa, T Ngara, K Tanabe) (Intergovernmental Panel on Climate Change)

IPCC (2007) 'Climate change 2007: the physical science basis.' Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. (Cambridge University Press: Cambridge, UK)

Koch P, Salou T (2013) 'AGRIBALYSE: methodology report. Version 1.1.' (ADEME: Angers, France)

Mathot M, Decruyenaere V, Stilmant D, Lambert R (2013) Contrasted greenhouse gas emissions from sored solid manure produced in tie-stall and deep litter barns. In 'Emissions of gas and dust from livestock'. Edn IFIP-Institut du Porc – 1er trimestre 2013. (Eds M Hassouna, N Guigand) pp. 67–70. (INRA: Rennes, France; *and* IFIP: Le Rheu, France)

Nemecek T, Kägi T (2007) Life cycle inventories of Swiss and European agricultural production systems. Final report ecoinvent V2.0 No. 15a. Agroscope Reckenholz-Taenikon Research Station ART, Swiss Center for Life Cycle Inventories, Zurich and Dübendorf, CH.

Nguyen TTH, van der Werf HMG, Eugène M, Veysset P, Devun J, Chesneau G, Doreau M (2012) Effects of type of ration and allocation methods on the environmental impacts of beef-production systems. *Livestock Science* **145**, 239–251. doi:10.1016/j.livsci.2012.02.010

Nijdam D, Rood T, Westhoek H (2012) The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Policy* **37**, 760–770. doi:10.1016/j.foodpol.2012.08.002

Pelletier N, Pirog R, Rasmussen R (2010) Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. *Agricultural Systems* **103**, 380–389. doi:10.1016/j.agsy.2010.03.009

Pré (2013) 'SimaPro 8.0.4.30.'

R Core Team (2014) 'R: a language and environment for statistical computing.' (R Foundation for Statistical Computing: Vienna) Available at http://www.R-project.org/ [Verified 15 December 2015]

Smith P (2014) Do grasslands act as a perpetual sink for carbon? *Global Change Biology* **20**, 2708–2711. doi:10.1111/gcb.12561

Soussana J-F, Lemaire G (2014) Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. *Agriculture, Ecosystems & Environment* **190**, 9–17. doi:10.1016/j.agee.2013.10.012

Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C (2006) 'Livestock's long shadow: environmental issues and options.' (Food and Agriculture Organisation/Livestock Environment and Development, Rome, Italy)

Tamminga S, Van Straalen WN, Subnel APJ, Meijer RGM, Steg A, Wener CJG, Block MC (1994) The Dutch protein evaluation system: the DVE/OEB system. *Livestock Production Science* **40**, 139–155. doi:10.1016/0301-6226(94)90043-4

Thoma G, Jolliet O, Wang Y (2013) A biophysical approach to allocation of life cycle environmental burdens for fluid milk supply chain analysis. *International Dairy Journal* **31**, 41–49. doi:10.1016/j.idairyj.2012.08.012

van Dooren C, Marinussen M, Blonk H, Aiking H, Vellinga P (2014) Exploring dietary guidelines based on ecological and nutritional values: a comparison of six dietary patterns. *Food Policy* **44**, 36–46. doi:10.1016/j.foodpol.2013.11.002

Van Soest PJ, Robertson JB, Lemis BA (1991) Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science* **74**, 3583–3597. doi:10.3168/jds.S0022-0302(91)78551-2

Van Vliet J (1997) Energy and protein standards with respect to the nutritional requirements of dairy heifers, CVB-report no. 19. IKC-Landbouw, Ede. [In Dutch]