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Environmental footprint of the integrated France–Italy beef production system assessed through a multi-indicator approach

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ABSTRACT

This study aims to evaluate the environmental footprint of the integrated France–Italy beef production system (extensive grassland-based suckler cow-calf farms in France with intensive cereal-based fattening farms in northeastern Italy) using a multi-indicator approach, which combines environmental impact categories computed with a cradle-to-farm gate Life Cycle Assessment, and food-related indicators based on the conversion of gross energy and protein of feedstuffs into raw boneless beef. The system boundaries were set from the calves' birth to their sale to the slaughterhouse, including the herd management, on- and off-farm feed production and materials used on the farms. One kilogram of body weight (BW) sold was used as the functional unit. The study involved 73 Charolais batches (i.e., a group of animals homogenous for age, finishing period and fattening farm), kept at 14 Italian farms. Data from 40 farms originating from the Charolais Network database (INRA) were used to characterize the French farm types, which were matched to the fattening batches according to the results of a cluster analysis. The impact categories assessed were as follows (mean ± SD per kg BW): global warming potential (GWP, 13.0 ± 0.7 kg CO_2-eq, reduced to 9.9 ± 0.7 kg CO_2-eq when considering the carbon sequestration due to French suckler cow-calf system permanent grassland), acidification potential (AP, 193 ± 13 g SO_2-eq), eutrophication potential (EP, 57 ± 4 g PO_4-eq), cumulative energy demand (CED, 36 ± 5 MJ), and land occupation (LO, 18.7 ± 0.8 m^2/year). The on-farm impacts outweighed those of the off-farm activities, except in the case of CED. On average, 41 MJ and 16.7 kg of dietary feed gross energy and protein were required to provide 1 MJ or 1 kg of protein of raw boneless beef, respectively, but nearly 85% and 80%, respectively, were derived from feedstuffs not suitable for human consumption. Emission-related (GWP, AP, EP) and resource utilization categories (CED, LO) were positively correlated. Food-related indicators showed positive correlations with emission-related indicators when the overall feedstuffs of the diet were considered but negative correlations when only the potentially human-edible portions of the beef diets were considered. In conclusion, the integration of the pasture-based France suckler cow-calf system with the cereal-based Italian fattening farms allows for the exploitation of the resources available, increasing the share of non-human-edible feedstuffs while maintaining good livestock productive efficiency. Combining indicators of impact categories with indicators of feed net supply may improve the assessment of the environmental footprint of livestock systems.

1. Introduction

Several studies have recognized beef production systems as important contributors to agricultural emissions of climate-altering, acidifying and eutrophying compounds, as well as to the exploitation of natural resources (Steinfeld et al., 2006; de Vries and de Boer, 2010, Gerber et al., 2013). At the same time, beef production systems produce a variety of positive outputs, contribute to food security and to the recycling of nutrients contained in feeds non-edible by humans into high-protein food of valuable nutritional quality (Oltjen and Beckett, 1996; Schiere et al., 2002; FAO, 2007; Ertl et al., 2016).

Different methods have been developed to evaluate the sustainability of the livestock sector, ranging from farm characteristics predictors to effect-based indicators (Lebacq et al., 2013). Among these, Life Cycle Assessment (LCA; ISO, 2006; Finnveden et al., 2009) has emerged as one of the most suited methodologies for evaluating the

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environmental impact of livestock systems (De Vries and de Boer, 2010; Lebacq et al., 2013). However, the LCA methodology usually does not account for some essential benefits of the beef production systems, such as the contribution to food security and the diverting of non-human-edible foodstuffs to animal feeding (Gill et al., 2010; Wilkinson, 2011). Therefore, approaches based on the use of different indicators could improve the assessment of livestock systems, particularly when different agro-ecosystems are involved in the production cycle (Cucek et al., 2012; Röös et al., 2013). This is the case in the integrated France–Italy beef production system. This system is characterized by a geographical separation of the grassland-based suckler cow-calf phase, mainly located in the French Massif Central semi-mountainous area (Brouard et al., 2014), and the intensive, cereal-based fattening phase, located in northeastern Italy, where intensive beef fatteners import the young bulls and rear them using total mixed rations based on maize silage and concentrates (Gallo et al., 2014). Different surveys have described various aspects of the system (Xiccato et al., 2005; Sturaro et al., 2009; Brouard et al., 2014; Gallo et al., 2014), but a comprehensive assessment of its sustainability is still lacking.

The aim of this study was to evaluate the environmental footprint of the integrated France–Italy beef production system using a multi-indicator approach, which combines emission-related – global warming (GWP), acidification (AP) and eutrophication (EP) potentials – and resource utilization – cumulative energy demand (CED) and land occupation (LO) – impact categories computed using a cradle-to-farm gate LCA methodology with food-related indicators (gross energy and protein conversion ratio and competition with direct human use of potentially human-edible feedstuffs).

2. Materials and methods

2.1. Goal and scope definition

The parameters of the LCA model for assessing the environmental footprint of the integrated France–Italy beef production system were set as follows. A cradle-to-farm gate LCA model was considered, taking into account the fattening batch as reference unit. The batch is defined as a group of stock calves, homogeneous for genetic type, origin, finishing herd, fattening period, and characteristics of the diet. The time period of each batch consisted of the whole productive cycle, from the birth of the calves to the sale of beef bulls to the slaughterhouse. Therefore, the system boundaries included the French suckler cow-calf herd, the Italian fattening phase and the transport from France to Italy. The impacts due to the herd management, the production of on- and off-farm feedstuffs, the production and use of industrial (fuel, plastic, lubricant) and bedding materials and the transport of inputs and animals (Fig. 1) were taken into account for both the French suckler cow-calf and the Italian fattening phases. The impact categories assessed were GWP, AP, EP, CED and LO and their magnitude was reported to 1 kg of body weight (BW) sold, which was taken as the functional unit. Land occupation was partitioned according to the agronomic destination: land surface area maintained as grassland (LO grass), land surface area cultivated for producing feedstuffs directly used for feeding animals (LO cropland), and the share of land surface area economically allocated to the production of agricultural by-products used in the beef diets (LO by-products).

Being the suckler cow-calf phase a multi-functional system producing more than one product, such as weaned male and female calves and cull cows, the allocation problem was resolved applying a mass allocation method. As the results of the LCA approach could be influenced by the allocation method chosen (ISO, 2006), a sensitivity analysis was performed by also considering an allocation of the impacts based on a protein method (relative importance of the protein in BW sold) and an economic method (relative importance of the revenue obtained by the sale of animals). For details, see Supplementary Table 1.

2.2. Life cycle inventory and life cycle impact assessment

2.2.1. Data collection and editing for the northeastern Italy fattening sector

The starting Italian dataset included 137 Charolais young bull batches. As the usual calving period in the French suckler cow-calf system is concentrated between November and April (Brouard et al., 2014), for this study, only the Italian batches of young bulls born in these months were retained. This editing provided 73 batches involving 4882 animals herded in 14 intensive beef fattening farms in northeastern Italy. For each farm, the land surface area used for the production of feedstuffs and the spreading of manure, the herd size, the use of chemical fertilizers and concentrates, and the amount of bedding materials, fuel and electricity consumed were collected by a unique operator through farm visits. The allocation of the different inputs to each batch within the farm was based on the utilization of each on-farm feed into the diet (agricultural inputs) and on the average amount of input per animal and per day (bedding and industrial inputs). Information collected for each batch included the number of animals, the purchase and sale dates and BW at the purchase in France (BWS), at the arrival to the Italian fattening farm (BWI) and at the end of the finishing period (BWF). The average daily gain (ADG, kg/day) was calculated as the difference between BWF and BWI divided by the total animal presence (animals × days).

Diet formulation and feed allowance, assumed equal to feed intake, were collected monthly for each diet used within each farm. All diets were sampled at the manger for the chemical composition analysis. Crude protein, ether extracts, crude fiber, ash, starch, neutral detergent fiber and non-starch carbohydrate content were assessed using the near-infrared spectroscopy method, whereas phosphorus (P) content was assessed according to the AOAC (2003) procedure (AOAC 999.10, 2000 and ICP-OES). Total monthly feed intake was calculated for each batch as the mean of two subsequent recorded daily feed intakes multiplied by the number of days between the two recordings. The feed intake in the period following the arrival of the batch at the farm was assumed equal to that of the first record, and that in the period preceding the sale of the batch to the slaughterhouse was assumed equal to the last recorded. The total feed intake for each batch (kg DM) was calculated as the sum of the monthly feed intakes and referred to the entire fattening period (sale date–arrival date), and the daily dry matter intake (DMI, kg DM/animal/day) was computed as the total feed intake divided by the length of the fattening period. The share of the maize silage in the DMI and the share of the dry matter ration produced on-farm (self-sufficiency rate) were also computed for each batch. Descriptive statistics of the Italian beef fattening farms and of the main traits of beef batches are given in Table 1, whereas the composition and characteristics of fattening diets are shown in Supplementary Tables 2 and 3, respectively, and the agricultural inputs for on-farm feedstuffs production are given in Supplementary Table 4.

The gross and digestible energy contents of the diets were calculated according to INRA (2007). The nitrogen (N) input-output flow was calculated for each batch according to the guidelines for the calculation of manure N production to be used within the framework of the European Union (EU) Nitrates Directive (Ketelaars and Van der Meer, 1999). The N intake was computed as the average daily DMI × finishing duration × average N content of the diet; the N retention was ((BWF − BWI) × 0.027 kg N/kg BW); and the N excretion was the difference between N intake and N retention. The excretion of P was calculated using the same procedure, with the average P dietary content and a retention factor of 0.0075 kg P/kg BW (Whiters et al., 2001).

2.2.2. Connection of the French beef suckler cow-calf and Italian beef fattening databases

The French data originated from the Charolais Network database of the INRA (Liénard et al., 1998) and concerned 40 suckler cow-calf farms surveyed annually. As stock calves from French beef suckler herds are usually collected by brokers who set up batches to be sold to Italian

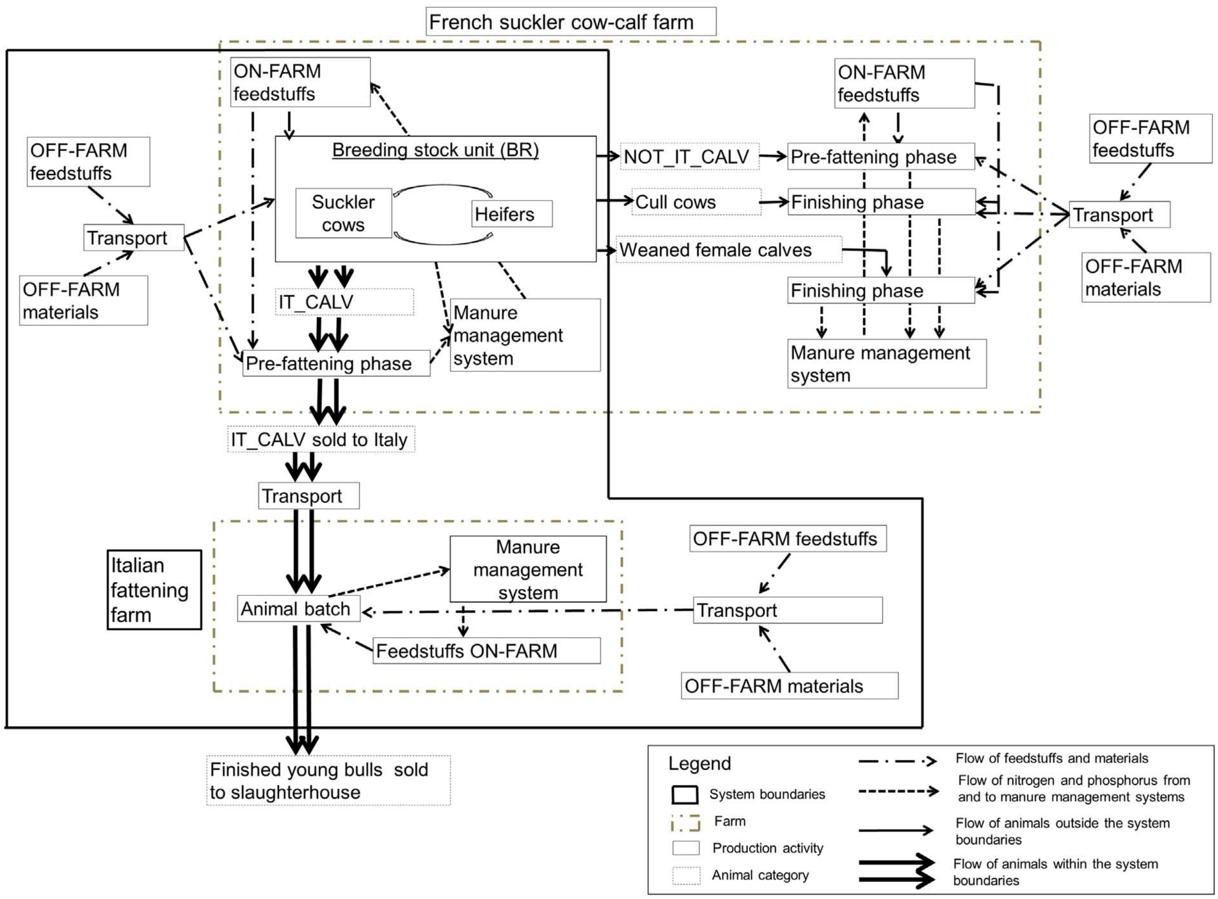

Fig. 1. Cradle-to-farm gate system boundaries of the integrated France–Italy beef production system.

fatteners, it was impossible to establish a direct connection between a specific French suckler cow-calf herd and a specific Italian fattening batch. With the aim of joining the French and Italian phases, the following procedure was developed. Since the main beef classification criteria for setting up homogeneous batches at the sale to Italy is the BWS, and the farm management in France is strongly linked to the calving period, these variables were used as classification criteria for clustering. The age at sale was also considered to obtain homogenous groups. A cluster analysis (PROC FASTCLUS procedure, SAS, 2012) of the fattening batches based on calving date, BWS and age at the sale to Italy was first performed. This analysis grouped the batches into three clusters differing mainly for calving season, i.e., early (November/December), mid (January/February), and late (March/April) winter. Descriptive statistics for the BWS, age and ADG of the three clusters are given in Supplementary Table 5. Then, the French farms were classified into 3 classes according to their predominant calving season and were connected to the Italian clusters having the same calving season (e.g., French farms having predominantly early winter calving season were connected with the early winter calving season cluster of batches). Finally, for each suckler cow-calf farm, the beef calves were classified as suitable to be retained in the Italian cluster (IT_CALV) according to the following criteria: i) calving dates included within the interval of the connected calving season; ii) BWS and age at sale included within the average ± 1 standard deviation for BWS and age of the corresponding Italian cluster. The remaining beef calves of each suckler cow-calf farm were classified as sold to other destinations (NOT_IT_CALV). All French farms with < 50% of IT_CALV were excluded from the analysis. The final French data set included 21 farms (10 early, 7 mid, and 4 late winter calving). The average farm data for each class of calving season were used to create the three suckler cow-calf farm types used to calculate the impact category values for the French suckler cow-calf system.

2.2.3. Suckler cow-calf herd system

The French suckler cow-calf system was modelled using farm observations available from yearly surveys in the INRA Charolais Network (Liénard et al., 1998). For each suckler cow-calf farm type, data about herd management, the use of inputs (concentrates, fertilizers, fuel, plastic, bedding straw), land surface area (extension of grassland, percentage of grassland area destined to hay and grass silage, extension of maize cropland) and outputs were used (Table 2). The herd management was modelled to have a steady-state situation during 1 year and to account for the farm output, represented by the sale of the different animal categories (Fig. 1). Suckler cows, (primiparous, secondiparous and multiparous, with a lactating and a not-lactating period), replacement heifers, breeding bulls and birth-to-weaning calves were included in the breeding stock unit (BR). Five animal categories resulted from the BR as outputs: IT_CALV, NOT_IT_CALV, female calves exceeding the replacement needs, cull cows and cull breeding bulls. Female and male calves exited from the BR at weaning, whereas cull cows exited at calf death or at calf weaning, according to the calves' mortality and the replacement rates. A pre-fattening period (from weaning to the sale) was considered for IT_CALV and NOT_IT_CALV to produce calves with BW and an age comparable to those found in the fattening herds of the destination. During finishing, primiparous and multiparous cull cows were assumed to gain 1.20 and 1.30 kg BW/d, respectively (INRA technical staff, personal communication), whereas the duration of the finishing period was set to achieve a mean BW at culling comparable to the values found for this category in each French farm type. The age and average BW at the sale of the post-weaned heifers intended for meat production were determined according to the average proportion of heifers sold at 1, 2 or 3 years of age

Table 1
Descriptive statistics (mean ± standard deviation) for the Italian beef fattening farms (N = 14) and the beef batches (N = 73).

Variable	Unit	Mean	SD
Farm features			
Farm AA[a]	ha	114	74
Herd AA[b]	ha	90	38
Herd size	Animals/year	708	281
Chemical fertilizer			
Nitrogen	kg/ha	80	17
P_2O_5	kg/ha	2	6
Concentrates	kg DM/LU[c]	1588	430
Bedding straw	kg/animal/year	56	67
Bedding sawdust	kg/animal/year	5	18
Bedding maize stover	kg/animal/year	18	45
Fuel	L/animal/year	50	40
Electricity	kWh/animal/year	26	10
Batch features			
Batch size	Animals, N	66	33
BWS[d]	kg/animal	405	13
BWI[e]	kg/animal	387	13
BWF[f]	kg/animal	731	19
ADG[g]	kg/day	1.52	0.09
Length of fattening	days	226	11
DMI[h]	kg DM/animal/day	10.6	0.5
% maize silage in diet	% DM	28	5
% self-sufficiency rate[i]	% DM	44	11

[a] Farm AA: farm agricultural area (total agricultural surface destined to herd manure spreading).
[b] Herd AA: herd agricultural area (total agricultural surface for producing the on-farm feedstuffs).
[c] LU: livestock unit, defined following the EU livestock schemes (cattle > 2 years = 1 LU, cattle 6 months to 2 years = 0.6 LU).
[d] BWS: body weight of the pre-fattened young bulls at the sale from France to Italian beef fattening farm.
[e] BWI: body weight of the pre-fattened young bulls at the arrival to Italian beef fattening farm.
[f] BWF: body weight of the young bulls at the end of the fattening period.
[g] ADG: average daily gain.
[h] DMI: dry matter intake (average composition: 28% maize silage, 13% maize grain, ground, 10% maize grain silage, 10% protein/mineral supplement, 8% maize gluten meal, 7% dried sugar beet pulp; for the complete average diet see Supplementary Table 3).
[i] % self-sufficiency rate of diet = total DMI produced on-farm / total DMI.

Table 2
Descriptive statistics (mean ± standard deviation) for the French suckler cow-calf farms according to the prevalent farm calving season.

Variable	Unit	Calving season		
		November/ December	January/ February	March/April
Farms	N	10	7	4
Farm AA[a]	ha	171 ± 96	159 ± 55	144 ± 57
Herd AA[b]	ha	112 ± 44	114 ± 31	116 ± 27
Grassland	ha	111 ± 44	114 ± 31	113 ± 22
– Grass silage	ha	10 ± 13	9 ± 10	21 ± 30
– Hay	ha	37 ± 16	38 ± 17	52 ± 17
Maize (silage)	ha	1 ± 3	0	3 ± 6
LU[c]	N	122 ± 45	134 ± 25	147 ± 76
Pregnant suckler cows	N	78 ± 26	87 ± 21	93 ± 73
Calvings	N	82 ± 27	90 ± 20	96 ± 73
Mortality[d]	%	8.2 ± 2.9	8.3 ± 5.1	12.6 ± 5.1
Prolificacy[e]	%	105.3 ± 2.9	103.8 ± 3.6	103.8 ± 3.2
Gestation[f]	%	93.1 ± 3.5	94 ± 5.8	90.7 ± 7.1
Productivity[g]	%	89.4 ± 5.6	88.1 ± 8.6	82.2 ± 7.8
Replacement[h]	%	23.5 ± 6.9	28.6 ± 21.4	22.5 ± 7.7
Animal output	kg BW sold/LU	314 ± 30	310 ± 27	259 ± 48
BW cull cow	kg BW	698 ± 49	710 ± 56	678 ± 39
Chemical fertilizers				
– Nitrogen	kg/ha	20 ± 22	34 ± 40	31 ± 33
– P_2O_5	kg/ha	12 ± 10	11 ± 9	43 ± 53
– K_2O	kg/ha	9 ± 8	9 ± 10	18 ± 15
Concentrates[i]	kg DM/ LU	630 ± 173	608 ± 236	541 ± 201
Bedding straw	kg/LU	293 ± 210	152 ± 175	157 ± 104
Fuel	L/LU	76 ± 18	57 ± 10	70 ± 26
Electricity	kWh/LU	106 ± 76	100 ± 60	100 ± 55

[a] Farm AA: farm agricultural area.
[b] Herd AA: herd agricultural area (total agricultural surface dedicated to suckler cow-calf herd management).
[c] LU: livestock unit, defined following the EU livestock schemes (cattle > 2 years = 1 LU, cattle 6 months to 2 years = 0.6 LU).
[d] Mortality: total pre-weaned calves dead during the year / total calves born in the year.
[e] Prolificacy: total calves born in the year / total pregnant suckler cows.
[f] Gestation: total pregnant suckler cows in the year / total suckler cows in the year.
[g] Productivity: total weaned calves in the year / total suckler cows in the year.
[h] Replacement: total cull cows / total pregnant suckler cows.
[i] Concentrates: wheat grain 75%, soybean meal 25%.

found in each farm type. Total feed intake for each French farm type (tDMI, kg DM/herd; see Supplementary Table 6a, b, c) was calculated as follows: using the data from Nguyen et al. (2012) we assumed a feed intake of 5000 kg DM/year for a livestock unit (LU), defined as a suckler cow of 750 kg BW. This value was adjusted to the average BW of suckler cows found in each French farm type, and then multiplied by the number of LU to obtain the tDMI of each farm type. The tDMI was then partitioned into each animal category on the basis of the share of each category to the total LU of each farm type.

The diet composition was split between the summer (pasture, from 1st April to 30th October) and the winter periods (from 1st November to 31st March), according to the most common management practices observed in Central France (Brouard et al., 2014). The summer diet of all the animals, with the exception of the calves, was based only on grass at pasture, and the intake was calculated at the month level as (Feed Intake Capacity / Grass Fill Unit) × 0.9 (INRA, 2007). The values for feed intake capacity were calculated using the equation $0.035 \times (BW_m)^{0.9}$ (Brouard et al., 2014), where BW_m was the monthly mean BW, whereas the values for the grass fill unit were obtained from INRA (2007). Winter diets were based on the rations available in Brouard et al. (2014), and the intake of winter DM was computed as the difference between the tDMI and the summer DMI.

Weaning of calves was assumed to occur at 256 d of age, and pre-weaning winter and summer diets were modelled using information from Brouard et al. (2014), considering the growth rate, the sex and the relative use of concentrates observed in each French farm type. The chemical composition of summer and winter diets for all the animal categories was calculated according to INRA (2007), whereas nitrogen and P input/output flows were estimated according to the same procedure used for the Italian phase, deriving the nitrogen content in the BW from Garcia et al. (2010).

2.3. Computation of emissions, energy and land occupation

The impacts were assessed taking into account the on- and off-farm activities. The LCA model was applied to the suckler cow-calf and the fattening phases independently, and the impact computed for the French suckler cow phase was added to that calculated for the Italian fattening phase for each batch through the calculation of a BW-based factor (e.g., kg CO_2-eq/kg BW pre-fattened young bull sold to Italian fattening farms) for each impact category and each French farm type. Afterwards, the BW-based factor was multiplied by the batch total BWS according to the cluster in which the batch was inserted.

2.3.1. On-farm impact calculation

Equations for emission calculations related to the French suckler cow-calf and Italian fattening phases are shown in Supplementary Table 7. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) contributed to GWP. Emissions derived from manure management (CH_4 and N_2O) and agricultural soils (N_2O) were calculated using the International Panel on Climate Change (IPCC, 2006) Tier 2 equations. Computation of the enteric methane production was based on equation 9 proposed by Sauvant et al. (2011), for which the emission was a function of the daily DMI expressed as a percentage of the mean BW, moderated by the percentage of concentrates in the diet. The acidification potential category considered the impacts due to emissions of ammonia (NH_3), nitrogen oxides and sulphur dioxide (SO_2) that occurred at the barn, manure storage and crop fertilization steps and were computed using equations derived from IPCC (2006). Concerning the suckler cow-calf phase, the winter manure management was based on a deep bedding system (no mixing), whereas during summer, animal manure was deposited directly on the pasture. During the fattening period, the manure management systems were differentiated for each farm as either slurry or solid manure.

The leaching of N and the loss of P at soil level were assessed for determining the EP; the former was calculated as the difference between N input and N output (N harvested and lost into atmosphere) for cropland and using the equation proposed by Vertès et al. (1997) for grassland, while P loss was calculated using the equations derived from Nemecek and Kägi (2007).

The impact factors (IF) for agricultural inputs (fertilizers, pesticides, fuel, seeds) used for producing on-farm feedstuffs were derived from Ecoinvent (Ecoinvent Centre, 2015) and Agri-footprint (Blonk Agri-footprint, 2014) databases. The land surface area for each on-farm feedstuff (at suckler cow-calf and fattening step) was recorded and used for assessing the land use impact. Moreover, fuel used for handling animals was considered an on-farm input and IF values were derived from EEA (2013) and the Ecoinvent database. The conversion of each pollutant compound into the common unit of each impact category, relative to GWP, AP and EP, was based on the factors derived from Myhre et al. (2013) for GWP (common unit kg CO_2-eq; conversion factor: CO_2: 1, CH_4: 28, N_2O: 265) and Guinée et al. (2002) for AP and EP (SO_2-eq — SO_2: 1, NH_3: 1.88, NO_x: 0.7 and PO_4-eq — NO_x: 0.13, NH_3: 0.35, NO_3: 0.43, P: 3.06, respectively).

2.3.2. Off-farm impact assessment

The off-farm impacts encompassed purchased-feed production, industrial inputs production and use at farm level and transport of the different inputs (including transport of pre-fattened young bulls from central France to northeastern Italy). For the suckler cow-calf phase, France was considered the origin zone for wheat grain; soybean meal used during the suckler cow-calf and fattening periods was assumed to arrive from Brazil via Rotterdam; off-farm maize grain, maize and sugar beet by-products used during the Italian fattening period were assumed to come from the Ukraine (farmers' communication). The impact factors were derived by Ecoinvent and Agri-food print databases (economic allocation), except for the fuel refinement IF (O'Brien et al. 2010) and the electricity IFs, which were derived from Veysset et al. (2011) for the French suckler cow-calf step and from Caputo and Sarti (2015) for the Italian fattening step.

2.3.3. Carbon sequestration in permanent grassland

As permanent grasslands are reported to act as carbon sinks, the offsetting of GHG emissions should be taken into account for grassland-related farm systems (Gac et al., 2010; Soussana et al., 2010). Estimated values for the carbon sequestration capacity in different regions and ecological-climatic conditions have been reported (Schulze et al., 2009; Soussana et al., 2010). In this study, a carbon sequestration value of 570 kg C/ha/year was used, a value proposed as a mean value for the French permanent grasslands systems (Dollé et al., 2013). Conversely, the net carbon change of cropland soils in northeastern Italy has been assumed to be equal to zero.

2.4. Energy and protein feed conversion ratio

The efficiency to convert the gross energy and protein content of feeds into raw boneless beef has been used as food-related indicators for the integrated France–Italy beef production system.

The energy and protein (CP) content of feedstuffs were computed according to INRA (2007). The computation of the potentially human-edible fraction of the beef diets was based on the potentially human-edible factors derived from Wilkinson (2011). The contribution of the French and Italian phase to the overall gross energy and crude protein consumption, as well as to that due to the potentially human-edible fraction, was computed according to the same procedures used in the partition of emissions.

The beef raw boneless yield was computed considering a carcass yield of 0.59 (Valance et al., 2014) and a boneless fraction of the carcass of 0.81 (Wilkinson, 2011). The gross energy and protein content of the raw boneless beef were derived from the National Nutrient database for Standard Reference (USDA, 2013), using an average fat content of 16% (Albertí et al., 2008). The values of 10.67 MJ gross energy/kg of edible beef and 182.7 g crude protein/kg of edible beef were considered.

The gross energy and protein conversion ratios of feedstuffs into raw boneless beef were computed considering both the overall feeds in the beef diets (E_CR and CP_CR, respectively) and the potentially human-edible fraction only (HeE_CR and HeCP_CR, respectively).

2.5. Relationships between indicators

Relationships between emissions, energy, land occupation, and energy and protein feed conversion ratio were investigated at batch level using the Pearson's correlation factors (PROC CORR, SAS, 2012).

3. Results

The results obtained for the different impact categories are reported in Table 3. When compared to the Italian finishing phase, the French suckler cow-calf phase showed similar AP values, 15% and 48% greater EP and GWP values, respectively, but a much lower CED value. The French suckler cow-calf phase also exhibited a nearly 3.5 times greater LO value than the Italian phase. The vast majority of the total LO for the whole beef production cycle was grassland (78%), located in France, whereas the cropland area was mainly located in Italy. When the system was enlarged to consider the carbon storage function of the permanent grassland, the mean GWP for the whole production cycle decreased by nearly 24% (9.9 ± 0.7 kg CO_2-eq/kg BW, mass allocation method), with a nearly equal share for the French and Italian phases. The sensitivity analysis applied to the allocation method used to resolve the multi-functionality within the French suckler cow-calf system showed that the use of different allocation methods led to different absolute impact values, with the lowest figures for the impact categories estimated with the mass allocation method compared to the economic and protein methods (from 0% to + 6% and from + 12% to + 17%, respectively).

Taking into account the contribution of the different production steps (Table 4), the impacts related to the on-farm activities largely outweighed those ascribed to the off-farm activities for all the impact categories (the on-farm share ranged from 77% to 87% of the total impacts), except for the CED (25%). The large contribution of the on-farm activities to the overall impacts was firstly due to the importance of the French suckler cow-calf phase, which accounted for more than half the total emissions for GWP, AP and EP and for nearly three-quarters of the LO. Conversely, the share of the off-farm impact was dominated by the Italian fattening phase (75 to 90% of total off-farm impacts), which was responsible for more than half of the CED of the whole production cycle. Regarding the different production steps, the first contributor to GWP was the enteric methane emission, obviously

Table 3
Values of impact categories per kg body weight sold for the French suckler cow-calf (FRA), the Italian fattening phase (ITA) and the France–Italy integrated beef production system (FRA + ITA), computed using different allocation methods (M: mass, E: economic, P: protein allocation).

Phase	Allocation	GWP[a]	GWPnet[b]	AP[c]	EP[d]	CED[e]	LO[f]			
							Total	Grassland[g]	Cropland[h]	By-products[i]
		kg CO_2-eq		g SO_2-eq	g PO_4-eq	MJ	m^2/year			
FRA	M	14.8 ± 0.5	9.2 ± 0.5	187 ± 10	59 ± 3	18 ± 1	27.1 ± 1.0	26.4 ± 0.9	0.12 ± 0.03	
	E	15.0 ± 0.6	9.4 ± 0.5	189 ± 11	59 ± 4	19 ± 1	27.4 ± 1.1	27.0 ± 0.9	0.12 ± 0.04	
	P	16.8 ± 0.5	10.5 ± 0.5	212 ± 10	66 ± 4	21 ± 1	30.8 ± 0.9	30.5 ± 0.6	0.13 ± 0.04	
ITA		10.0 ± 1.1	10.0 ± 1.1	189 ± 23	51 ± 7	52 ± 12	7.7 ± 1.0		5.6 ± 0.9	1.9 ± 0.8
FRA + ITA	M	13.0 ± 0.7	9.9 ± 0.7	193 ± 13	57 ± 4	36 ± 5	18.7 ± 0.8	14.5 ± 0.8	2.7 ± 0.5	0.9 ± 0.4
	E	13.1 ± 0.8	10.0 ± 0.7	194 ± 13	57 ± 4	37 ± 5	18.9 ± 0.9	14.9 ± 0.8	2.7 ± 0.5	0.9 ± 0.4
	P	14.1 ± 0.8	10.6 ± 0.7	207 ± 13	61 ± 5	39 ± 5	20.8 ± 0.9	16.8 ± 0.8	2.7 ± 0.5	0.9 ± 0.4

[a] GWP: global warming potential.
[b] GWPnet: global warming potential adjusted for the carbon sequestration function due to permanent grasslands located in France.
[c] AP: acidification potential.
[d] EP: eutrophication potential.
[e] CED: cumulative energy demand.
[f] LO: land occupation.
[g] Grassland: grassland surface utilized for producing livestock feedstuffs.
[h] Cropland: cropland surface utilized for producing livestock feedstuffs (economic allocation).
[i] By-products: cropland surface utilized for producing the by-products obtained from other production cycles and included in the beef diet (economic allocation).

confined to the on-farm activities, followed by the feedstuffs production, irrespective of the impact origin (on- or off-farm). The transport, which was multi-connected especially with the off-farm feedstuffs production, had a notable share only for CED, whereas the contribution to the other impact categories was less important. The results for gross energy and protein conversion ratio are reported in Table 5. On average, the dietary feed gross energy requirement to provide 1 MJ of raw boneless beef was close to 41 MJ, which means that the energy conversion efficiency was close to 2.5%. However, when the gross energy requirement included only the potentially human-edible fraction of the diet, the dietary feed gross energy requirement decreased to nearly 6.4 MJ. To provide 1 kg of CP in raw boneless beef, we found a

Table 5
Gross energy (MJ) and protein (kg) required in the whole beef diet (E_CR and CP_CR, respectively) or in the potentially human-edible part of the beef diet (HeE_CR and HeCP_CR, respectively) to provide a MJ of gross energy or a kg of CP in raw boneless beef for the integrated France–Italy beef production system.

Item	Overall	French contribution	Italian contribution
E_CR, MJ/MJ	40.70 ± 1.90	29.37 ± 1.71	11.33 ± 0.75
HeE_CR, MJ/MJ	6.36 ± 0.71	2.40 ± 0.25	3.96 ± 0.66
CP_CR, kg/kg	16.70 ± 2.46	11.72 ± 2.42	4.98 ± 0.46
HeCP_CR, kg/kg	3.29 ± 0.42	1.55 ± 0.26	1.74 ± 0.29

Table 4
Contribution (%) to the impact categories of on- and off-farm production steps for the integrated France–Italy beef production system ($N = 73$, only mass allocation method was used in the computations).

	GWP[a]	AP[b]	EP[c]	CED[d]	LO[e]
On-farm	79.5 ± 3.7	86.6 ± 3.1	77.2 ± 4.9	24.7 ± 5.3	83.6 ± 3.7
France	59.1 ± 2.9	51.8 ± 2.8	54.3 ± 3.2	15.6 ± 2.5	78.7 ± 2.8
Enteric fermentation	41.6 ± 2.0				
Manure management	4.3 ± 0.2	13.7 ± 1.3	10.4 ± 0.9		
Fuel for herd/manure management	< 1.0	< 1.0	< 1.0	5.9 ± 1.5	< 1.0
Feed production	12.2 ± 0.9	38.0 ± 2.5	43.8 ± 2.7	9.7 ± 2.5	78.6 ± 2.8
Italy	20.4 ± 2.3	34.8 ± 3.8	22.9 ± 4.2	9.1 ± 4.1	4.9 ± 1.8
Enteric fermentation	13.8 ± 1.2				
Manure management	3.7 ± 1	28.7 ± 2.6	15.2 ± 1.5		
Fuel for herd/manure management	< 1.0	< 1.0	< 1.0	3.7 ± 2.2	< 1.0
Feed production	2.3 ± 0.9	6.1 ± 2.7	7.6 ± 3.6	5.4 ± 2.9	4.8 ± 1.8
Off-farm	20.5 ± 3.7	13.4 ± 2.9	22.8 ± 4.9	75.3 ± 5.5	16.4 ± 3.3
France	4.9 ± 0.8	2.3 ± 1.1	3.6 ± 1.6	17.4 ± 4.1	2.1 ± 0.5
Feed production	3.5 ± 0.4	< 1.0	< 1.0	4.9 ± 1.0	< 1.0
Transport	< 1.0	< 1.0	< 1.0	3.7 ± 0.6	< 1.0
Materials	< 1.0	< 1.0	< 1.0	7.9 ± 2.2	< 1.0
Bedding materials	< 1.0	1.6 ± 1	3.1 ± 1.5	< 1.0	1.8 ± 0.4
Italy	15.6 ± 4	11.1 ± 3	19.3 ± 5.1	57.9 ± 8.1	14.3 ± 3.3
Feed production	10.6 ± 3.1	9.0 ± 2.7	17.0 ± 4.9	35.3 ± 6.2	13.6 ± 3.3
Transport	3.7 ± 0.9	1.3 ± 0.3	1.1 ± 0.3	21.8 ± 3.5	< 1.0
Materials	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0
Bedding materials	< 1.0	< 1.0	1.1 ± 1.4	< 1.0	< 1.0

[a] GWP: global warming potential.
[b] AP: acidification potential.
[c] EP: eutrophication potential.
[d] CED: cumulative energy demand.
[e] LO: land occupation.

Table 6
Pearson's correlation factors for the impact categories and the food-related indicators calculated for the France–Italy beef production system (N = 73; values below diagonal indicate coefficients of correlation, values above diagonal indicate P value).

	GWP	AP	EP	CED	LO	E_CR	HeE_CR	CP_CR	HeCP_CR
GWP[a]		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.002	< 0.001	0.000
AP[b]	0.78		< 0.001	0.003	0.017	< 0.001	0.006	< 0.001	0.001
EP[c]	0.87	0.93		< 0.001	0.013	< 0.001	0.001	< 0.001	< 0.001
CED[d]	0.78	0.34	0.56		< 0.001	0.063	0.071	0.953	0.076
LO[e]	0.53	0.28	0.29	0.44		0.284	0.157	0.028	0.042
E_CR[f]	0.68	0.82	0.82	0.22	0.13		0.002	< 0.001	< 0.001
HeE_CR[g]	− 0.36	− 0.32	− 0.37	− 0.21	0.17	− 0.36		0.055	< 0.001
CP_CR[h]	0.50	0.67	0.58	0.01	0.26	0.61	− 0.23		< 0.001
HeCP_CR[i]	− 0.41	− 0.40	− 0.48	− 0.21	0.24	− 0.48	0.90	− 0.48	

[a] GWP: global warming potential.
[b] AP: acidification potential.
[c] EP: eutrophication potential.
[d] CED: cumulative energy demand.
[e] LO: land occupation.
[f] E_CR: gross energy conversion ratio (MJ gross energy in the diet/MJ gross energy in raw boneless beef).
[g] HeE_CR: potentially human-edible gross energy conversion ratio (MJ gross energy in the potentially human-edible fraction of the diet/MJ gross energy in raw boneless beef).
[h] CP_CR: protein conversion ratio (kg crude protein in the diet/kg protein in raw boneless beef).
[i] HeCP_CR: potentially human-edible protein conversion ratio (kg crude protein in the potentially human-edible fraction of the diet/kg protein in raw boneless beef).

dietary feed CP requirement of nearly 16.7 kg. Therefore, as expected, the conversion efficiency of dietary CP (close to 6%) was much greater than that of the dietary gross energy. On average, nearly 85% of the gross energy and nearly 80% of the CP required as feed to provide one unit of raw boneless beef derived from feedstuffs not suitable for human consumption. The French suckler cow-calf phase accounted for nearly 70% of the overall gross energy and protein intake required to provide one unit of raw boneless beef. However, the Italian phase showed a greater consumption of potentially human-edible feedstuffs and contributed to over 60% and 53% of the gross energy and protein intake of such feeds, respectively.

The impact categories (Table 6) were positively correlated (from $r = 0.28$ to $r = 0.93$, $P < 0.01$), with greater values for the impact categories related to pollutant emissions (GWP, AP and EP) than for those related to resource utilization (CED and LO). The conversion ratio indicators showed strong positive correlations with emission-related impact categories (Pearson's r: from 0.50 to 0.82, $P < 0.001$) when computed considering the overall feedstuffs used in the diet. Conversely, when only the potentially human-edible part of the beef diets was considered, the feed conversion ratio was negatively correlated with the emission-related impact categories (− 0.32 to − 0.48, $P < 0.001$). The CED did not show a relationship with the feed conversion indicators, whereas LO was positively correlated only with CP food-related indicators.

4. Discussion

4.1. Emission-related impact categories

The emission-related impact categories assess the impact caused by the release of environmentally active compounds into the environmental compartments. Several studies have evaluated these impact categories concerning the beef production system using a cradle-to-farm gate LCA. The results for the GWP found in this study were comparable to those found for the fattened bulls in the French beef sector – 14.2 (Gac et al., 2010), 13.2 (Nguyen et al., 2012), 13.8 (Dollé et al., 2013) and 12.8 kg CO_2-eq/kg BW (Veysset et al., 2014) – and were in the range of values reported by other studies conducted in the EU or extra-EU countries (de Vries et al., 2015). Concerning the other impact categories, the mean value found for AP was greater than those reported by Nguyen et al. (2012) and Lupo et al. (2013), probably due to the difference in the volatilization factors used, whereas EP was within the range of variation shown by other studies (Pelletier et al., 2010; Nguyen et al., 2012). Differences in emission values between the French and the Italian phases were evident for the GWP only. However, these differences disappeared when the carbon sequestration of the permanent grassland was included in the computation of the GWP.

Emissions due to on-farm activities largely exceeded those due to off-farm activities. This predominance was particularly evident for the French phase and can be explained considering that the main emission sources (enteric fermentation, manure management and on-farm feed production) are located within the farm. The beef production system typical of the French phase, which largely relies on grasslands with low input rates, tends to exacerbate the on-farm emission level of the suckler cow-calf phase, as the BW sold per LU is low and the roughage-based diets used for the suckler cows allocated to the pre-fattening young bulls increases the enteric fermentation emission (Sauvant et al., 2011; Crosson et al., 2011). Conversely, the more intensive and productive Italian fattening phase, while reducing the impacts per product unit, showed a lower diet self-sufficiency and a greater chemical fertilizer spreading (80 kg N/ha on-farm vs 20–34 kg N/ha for the Italian and French beef farms, respectively), which negatively affected the local nutrient balance.

When the carbon sequestration related to the permanent grassland was considered, GWP found in this study was greater than that reported by Morel et al. (2016) (9.9 vs and 7.6–8.2 kg CO_2-eq/kg BW), probably because the grassland surface area within the system in this study was lower than that found in Morel et al. (2016). The differences found in the carbon sequestration rate and in methods used to take into account the land-use change issue implicate a lack of standardization that has to be considered when including the carbon sequestration as a mitigation factor of GHG emissions due to the beef sector (Flysjö et al., 2011). Applying carbon sequestration values found in literature for the French permanent grasslands other than 570 kg C/ha/year which ranged from 200 kg C/ha/year (Dollé et al., 2009) to 780 kg C/ha/year (mean value derived from Allard et al., 2007), the net GWP found in this study ranged from 12.0 kg CO_2-eq/kg BW to 8.8 kg CO_2-eq/kg BW, respectively.

4.2. Resource utilization impact categories

The CED and LO categories are connected with the degree of resource use (ISO, 2006). The mean value for CED found in this study was comparable with values reported by Nguyen et al. (2012) and Pelletier et al. (2010) (35 and 38 MJ/kg BW, respectively), whereas Capper (2012) computed a much lower CED value of 7 MJ/kg BW. The most energy-demanding production steps were related to the off-farm fraction of the production cycle, first of all the production of the off-farm feeds and industrial materials, and the Italian fattening phase greatly outweighed the French suckler cow-calf phase. The predominance of the Italian fattening phase can be explained by the greater use of high energy-demanding concentrates and by the lower self-sufficiency of the diet, particularly for the share of concentrate feeds, which included imports of concentrates from other countries, with the consequent energy consumption during the transport activities.

Conversely, the LO mean result was similar to that found by Nguyen et al. (2012) – 21 m^2/year per 1 kg BW – and lower than the those obtained in LCA studies on beef production systems conducted in the USA and Canada – from 33 (Capper, 2012) to 56 m^2/year per 1 kg BW (Beauchemin et al., 2011). The LO category was much more related to the on-farm than the off-farm production steps, especially due to the French suckler cow-calf phase. The subdivision of the LO category showed how the majority of the land exploited by the integrated France–Italy beef production system was permanent grasslands located in the French Massif Central, an area with a low or no vocation for cultivated crops. When only cropland directly and indirectly used for producing feedstuffs was considered, the LO found in this study (3.6 ± 0.5 m^2/year per 1 kg BW) was similar or less than those found for monogastric (pig and poultry) meat production (Basset-Mens and Van der Werf, 2005; Gonzalez-García et al., 2015; Bava et al., 2015).

4.3. Gross energy and protein conversion efficiency

Few studies have assessed the conversion efficiency of dietary gross energy and protein into beef products taking into account also the proportion of potentially human-edible feeds of the beef diets (CAST, 1999; Pelletier et al., 2010; Wilkinson, 2011). A direct comparison for E_CR and HeE_CR is possible only with Pelletier et al. (2010), because Wilkinson (2011) used metabolizable energy and not gross energy. Gross energy is a direct measure that can be obtained through heat combustion, while metabolizable energy needs estimates of digestibility and methane and urinary energy losses. The conversion ratio of gross energy of the whole diet into gross energy of raw boneless beef found in this study was comparable to that reported by Pelletier et al. (2010) for the feedlot-finishing system in the upper mid-western United States, whereas our assessment of HeE_CR was lower than the values of Pelletier et al. (2010), due to the important share of maize silage in the beef diet of the integrated France–Italy beef production system against the high share of grains in the US feedlot system. The conversion ratio of CP of the whole diet into CP of raw boneless beef found in this study was an intermediate between the greater values found in suckler lowland farms by Wilkinson (2011), probably because of the lower level of production intensity of that scenario, and the lower values reported by CAST (1999). Despite the low global conversion efficiency of gross energy and CP into beef products of the French–Italy beef production system, only 15% of the gross energy and 20% of the CP content of feeds were from potentially human-edible ingredients. Moreover, the extensive partner of the beef production system, the French suckler cow-calf farms, accounted for nearly 70% of the total gross energy and CP required to produce a unit of raw boneless beef but nearly 90% of the gross energy and 85% of the CP used by the French farms were from human-inedible ingredients.

4.4. Integrated assessment of the environmental impact and conversion efficiencies

The strong and positive correlations between the different impact categories related to the emission of environmentally active compounds found in this study showed that they tend to assess the same dimension of the environmental impact of the integrated France–Italy beef production system. Moreover, the GWP category could be a proxy for the other impact categories, which showed correlations with GWP of 0.53 or more. However, AP and EP showed lower correlations with resource utilization impact categories (CED and LO), indicating that the latter may assess a second dimension of the environmental impact and should be considered when the environmental impact of the beef sector is assessed (Huijbregts et al., 2010; Röös et al., 2013).

Emission-related impact categories were positively correlated with the conversion ratio of gross energy and CP when considering the whole beef diet, but negatively correlated when only the potentially human-edible fraction of the beef diet was taken into account. The increase in the conversion efficiency of the feedstuffs has been correlated to the increase in the use of protein- and energy-concentrated feedstuffs (Steinfeld et al., 2006), most of which are potentially human-edible (e.g., maize grain, soy bean). Improving the conversion efficiency of dietary gross energy and CP may then decrease the emissions of environmentally active compounds but may at the same time lead to greater competition with grain production for human food consumption, giving rise to other environmental and ethical concerns (Garnett, 2011). Therefore, the potentially human-edible share of the beef diets should be considered so that the livestock's contribution to food security can be taken into account (Schader et al., 2015).

Finally, gross energy and protein conversion efficiency parameters were mostly independent from the resource utilization impact categories, even if an intermediate positive relationship has been observed between LO and CP_CR. The results suggest that the adoption of mitigation strategies aimed to decrease the amount of energy and land surface area needed for beef production could be feasible without increasing the share of potentially human-edible components of the beef diets.

5. Conclusions

This study aimed to assess the environmental footprint of the integrated France–Italy beef production system by combining environmental impact parameters computed using LCA methodology and food-related indicators based on the conversion ratios of gross energy and CP of feedstuffs into gross energy and CP of raw boneless beef products. This approach allowed for the appreciation of the magnitude of the different indicators of the beef chain considered, and their mutual relationships, highlighting in particular how the share of potentially human-edible feedstuffs into beef diets affects the emission-related environmental impact of beef production systems.

The suckler cow-calf beef production system located in areas of Central France characterized by low vocation for cultivated crops strongly contributes to keep the share of non-human-edible feedstuffs high, but at the same time, the cropland-oriented farms of North-East Italy are characterized by high level of beef productivity and good feed efficiency. For these reasons, the integration of the pasture-based France suckler cow-calf system with the cereal-based Italian fattening farms seems a good strategy in terms of exploitation of resources available.

The controversial relationships found between impact categories, resource utilization categories, and food-related indicators based on the whole beef diet or on the potentially human-edible fraction of the beef diet only suggest that policies and strategies aiming to improve the sustainability of beef production systems should be based on a multi-indicator approach.

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Appendix A. Supplementary data

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