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ABSTRACT

Four complete beef-production systems consisting each of two stages were compared. The systems were formed by combining two diets for the cow-calf herd with finishing heifers stage – St (Standard) and O3 (maximising omega-3 fatty acids (FAs) using wrapped grass silage) – with four diets for the bull-fattening herd stage — SM (silage maize starch), SML (silage maize starch plus linseed, rich in omega-3 FAs), FC (fibre-based concentrate), and SCL (starch-based concentrate plus linseed): St-SM, O3-SML, St-FC and O3-SCL. Life Cycle Assessments applied to these systems (from cradle to farm gate for a one-year period) estimated that their environmental impacts, per kg of carcass mass, ranged from 27.0 to 27.9 kg CO_2 equivalents (eq), 64.8–73.4 MJ, 94–98 g PO_4^{3-} eq, 168–173 g SO_2 eq, 47–48 m^2year for climate change (CC, not including effect of land use and land-use change, LULUC), cumulative energy demand (CED), eutrophication potential, acidification potential and land occupation, respectively. Consideration of LULUC decreased CC from 8 to 10%. Minor impact differences between these systems were observed, except for CED of St-FC, mainly because more energy was needed to dehydrate beet pulp and lucerne. CC of O3-SCL was 3% lower than CC of St-SM. Most of the environmental impacts of beef-production systems originated from the cow-calf herd with finishing heifers (73–97%), which indicates that research on the reduction of environmental impacts of this type of beef-production system should focus on this herd. For the cow-calf herd with finishing heifers, comparison of several allocation methods revealed that allocation method strongly affected the impacts per kg of carcass mass of the breeding bull and finished cull cows and, to a much lesser extent, those of fattened bulls and finished heifers. Consideration of both products (several animal types) and the ecosystem services supplied by these systems seems a promising perspective. This concept needs to be discussed and developed as an approach to consider the multi-functionality of farming systems.

1. Introduction

Worldwide the livestock sector was estimated to contribute 18% of global greenhouse gas (GHG) emissions, according to a Life Cycle Assessment (LCA) approach (Steinfeld et al., 2006). Methane (CH_4) is the most significant (58–63%) contributor to GHG emissions from beef systems (Veysset et al., 2010). Supplementation of diets with lipids is one of the most effective strategies for reducing enteric CH_4 emissions by ruminants (Beauchemin et al., 2009). Martin et al. (2008) reported that feeding lipids rich in omega-3 fatty acids (FAs) from linseed significantly decreased enteric CH_4 emissions from dairy cows. Enteric CH_4 production by bulls fed a high-concentrate

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diet based on cereals supplemented with extruded linseed was reduced by 23% (g/kg live weight gain) in comparison with a high-concentrate diet based on fibre-rich co-products (Eugène et al., 2011). However, CH_4 mitigation strategies must be assessed in a global vision of production systems to evaluate all GHG emissions and other environmental impacts (Martin et al., 2010).

In France, production systems for beef cows are based on grass, but fattening systems are diversified. For a same type of production, e.g. young bulls, there are several drivers for choosing a feeding system. The first one is the type of forage (based on grass or maize silage) and the proportion of forage relative to concentrate feed (Nguyen et al., in press). The second one is the nature of concentrates. Beef quality is a major consumer concern. A primary target in improving meat's nutritional quality is increasing its concentration of n-3 polyunsaturated fatty acids (FA) Doreau et al. (2011a). Indeed these FA play a role in the reduction of the risk of coronary heart disease and in infant development. Beef products can be enriched naturally with omega-3 FAs through provision of feed rich in linolenic acid, such as linseed, fresh grass or wrapped grass silage. Independently of meat quality, another strategy for beef fattening is the use of by-products rich in fibre, which avoids food competition with humans by reducing the use of cereals for animal feeding.

The main objective of this study was to investigate the environmental impacts, using a LCA approach, of a standard beef-production system in France by comparing two systems, one based on feed rich in omega-3 FA and one with co-products rich in fibre. These beef production systems corresponded to a grassland-suckler cow-calf herd with finishing heifers and a bull-fattening herd. Grassland-based production systems contribute to sustainable rural development due to the ecosystem services they provide: landscape quality, biodiversity and carbon (C) sequestration. An additional objective was to analyse different allocation methods used to attribute environmental impacts to the co-products delivered by production systems. The choice of allocation method has generated much discussion in LCA studies on dairy systems regarding the co-products of milk and meat. In our beef-production systems, co-products were the types of meats from fattened bulls, finished heifers, finished cull cows, and a breeding bull. Ecosystem services supplied by these grassland-based production systems can also be considered as a co-product; we will explore this option.

2. Materials and methods

2.1. Goal definition

The goal of this study was to investigate four beef-production strategies practised in France, two of which produce omega-3 FA-enriched beef. These systems were characterised according to ration strategies for the suckler cow-calf herd with finishing heifers and the bull-fattening herd. We analysed the effect of different allocation methods, such as economic allocation (including the provision of ecosystem services or not), mass allocation, and allocation based on protein content, on potential environmental impacts for each co-product delivered by the system.

2.2. Scope definition

2.2.1. Description of French beef production systems

Each of the four production systems (Fig. 1) consists of two herds. The suckler cow-calf herd with finishing heifers (to be designated as cow-calf herd in the rest of this paper) produces weaned male calves or pre-fattened bulls, finished heifers, finished cull cows and a breeding bull. The weaned male calves or pre-fattened bulls are transferred to the bull-fattening herd, which yields fattened bulls. The systems are based on the Charolais breed as it represents 40% of the French suckler-cow herd (Institut de l'Elevage, 2010). Two production methods were compared for the cow-calf herd. The first was the standard (St) cow-calf herd, which is most frequently practised in the Charolais basin. The second, the omega-3 (O3) cow-calf herd, aimed to maximise the animals' omega-3 FA intake by using wrapped grass silage, which can be easily adopted by farmers. Four production methods were compared for the bull-fattening herd. The first was a standard bull-fattening herd using a diet rich in starch based on silage maize (SM). The second was a bull-fattening herd using a diet rich in starch (based on silage maize) supplemented with linseeds (SML). The third was a bull-fattening herd using a fibre-based concentrate diet (FC). The last used a starch-based concentrate supplemented with a linseed diet (SCL). We combined the two herds to study the following four beef-production systems: 1) St-SM, 2) St-FC, 3) O3-SML, and 4) O3-SCL. All rations were formulated to satisfy beef-cattle nutrient requirements according to animal characteristics and feed-composition values, based on recommendations of INRA beef researchers and data tables (INRA, 2007). Details for both phases of the four systems are given below.

As suckler-cow farming practices in the Charolais basin are highly diverse, our systems were modelled based on “Charolais Beef Cattle Farm Networks” of the French Livestock Institute (Réseaux d'élevage Charolais, 2009) in consultation with beef researchers and experts. Both St and O3 cow-calf herds consist of 70 cows that annually provide 62 weaned calves (Table 1). The replacement rate, defined as the proportion of heifers replacing cull cows, was 23%. The cow-calf herd consists of four components for St and three components for O3. The first is reproduction; its output consists of weaned male calves, weaned female calves not used for replacement cull cows, cull cows and a breeding bull. The second component is rearing female calves from weaning (9 months) to finishing at 33 months. The third component is the finishing of cull cows, i.e. fattened before sending to the slaughterhouse. The last component (only for St) is pre-fattening of male calves for 2 months after weaning. The St and O3 cow-calf herd systems were built to reflect two types of actual farming practices which differ with respect to the calving period and the age at which male calves are sent to the bull-fattening herd. In the St, herd calves are born in February and weaned at 9 months, and male calves are pre-fattened for 2 months (reaching 430 kg live weight) with concentrate feed (20% crude protein) and hay before passing to the bull-fattening herd. In the O3, herd calves are born in January and weaned at 9 months, and male calves (350 kg live weight) are sent directly to the bull-fattening herd.

For feed management, both St and O3 are situated in the grassland zone of the Charolais basin and are classified as extensive systems with 1.2 livestock units per ha of forage area and 7.5 months grazing from April to November. One livestock unit is defined as an animal that consumes 5 t dry matter (DM)/year (Gac et al., 2010a). Indoors in winter, the St herd is fed with hay and concentrates (mainly based on cereals produced on-farm and a mix meal which consisted of 30% soybean meal, 40% rapeseed meal and 30% sunflower meal) produced off-farm, whereas the O3 herd is fed with wrapped grass silage, hay and concentrates (cereals and mix meal). Wrapped grass silage, i.e. grass silage at 55% DM covered by plastic, has a higher omega-3 FA content than hay (Arrigo, 2010). Cull cows are finished for 100 days with a concentrate diet and hay (St herd) or wrapped grass silage (O3 herd). Weaned female calves which are not destined to be used for replacement cows are reared as heifers to be used for replacement until 29 months and then finished at pasture supplemented with cereals over 4 months to produce finished heifers.

Pre-fattened bulls from St are finished in the SM and FC bull-fattening herds. Weaned male calves from O3 are finished in the SML and SCL bull-fattening herds. The SM herd was located in the Pays de la Loire region (western France), which is a cereal-producing region. This phase was modelled based on "Typical Case: Young bull-fattening in Pays de la Loire" of the farm networks of the French Livestock Institute (Sarzeaud et al., 2009). The pre-fattened male calves are fed a high-forage diet composed of 58% maize silage, 24% wheat, 15% soybean meal, 2% hay, and 1% minerals (DM basis), resulting in an average daily live weight gain (ADG) of 1.40 kg/d. The SML herd, also located in the Pays de la Loire region, is modelled on the SM herd with a portion of the wheat replaced by extruded linseed. The diet is composed of 58% maize silage, 17% wheat, 14% soybean meal, 8% Croquelin® (an extruded mix containing 50% linseed, 30% wheat bran and 20% sunflower meal, Valorex, Combourtillé, France), 2% hay, and 1% minerals (DM basis). We assumed that animals in the SML herd are provided the same quantity of net energy for growth (i.e. 63 MJ/d) as those in the SM herd. Since lipid supplementation is known to improve beef cattle performance (Clinquart et al., 1995) we assumed that the ADG of the SML herd (1.6% lipid added) animals is 5% higher than that of animals in the SM herd.

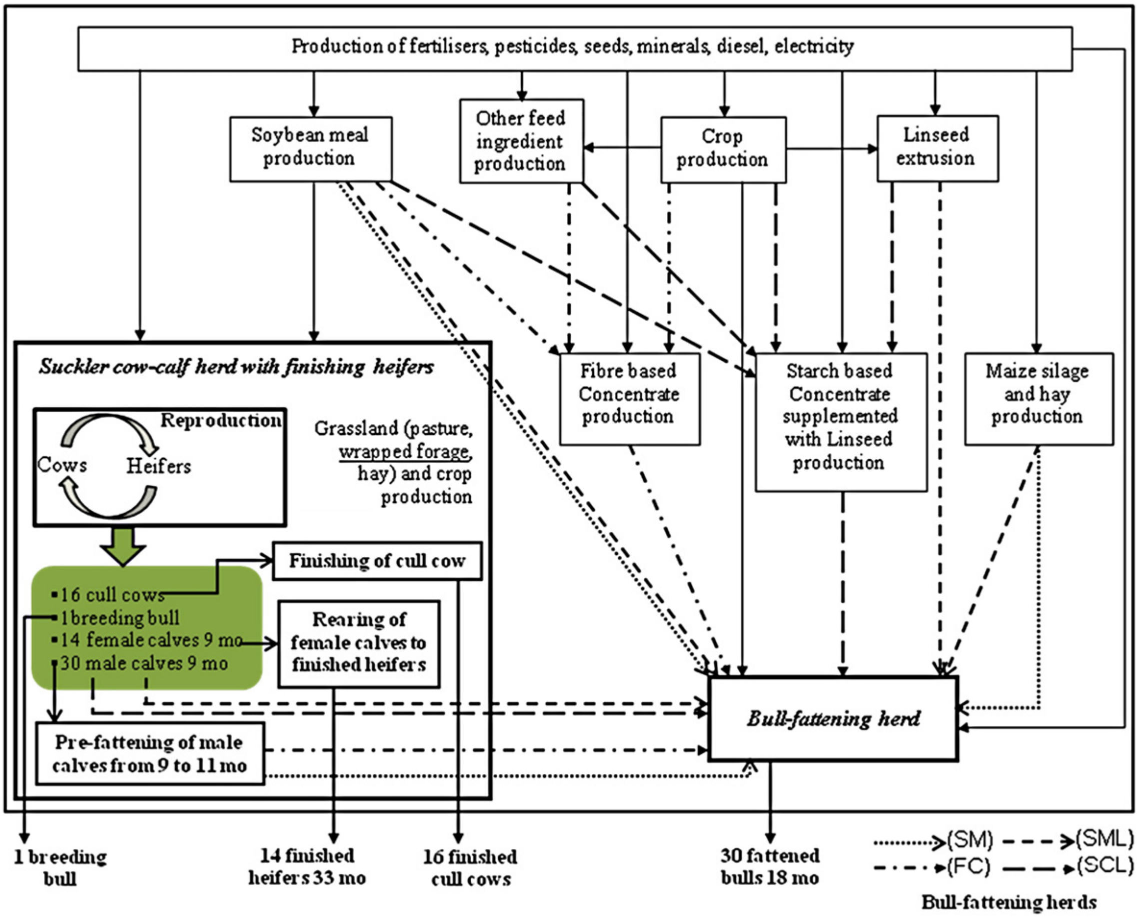

Fig. 1. "Cradle to farm-gate" life cycle of the four beef-production systems. St: Standard suckler cow-calf herd with finishing heifers. O3: Suckler cow-calf herd with finishing heifers enriched in omega-3 FAs through pasture and wrapped grass silage. SM: Standard bull-fattening herd using a diet rich in starch based on maize silage. SML: Bull-fattening herd using a diet rich in starch (based on maize silage) supplemented with linseeds. FC: Bull-fattening herd using a fibre-based concentrate diet. SCL: Bull-fattening herd using a starch-based concentrate supplemented with linseeds. Underline: Indicates this aspect is only present in O3 suckler cow-calf herd with finishing heifers. Pre-fattening of male calves from 9 to 11 months is only present in St suckler cow-calf herd with finishing heifers. ■ Allocation methods were applied for these animals of the common phase, i.e. the reproduction component, before passing to the other periods.

Table 1
Inputs and outputs of the four beef production systems.

Inputs (t dry matter)	St-SM	O3-SML	St-FC	O3-SCL
Feed for cow-calf herd with finishing heifers	St	O3	St	O3
Pastured grass	276.5	270.8	276.5	270.8
Hay	175.4	82.8	175.4	82.8
Wrapped grass silage	–	91.8	–	91.8
Cereals	76.5	66.9	76.5	66.9
Mix meal[a]	6.8	4.8	6.8	4.8
Feed for bull-fattening herd	SM	SML	FC	SCL
Maize silage	31.7	38.5	–	–
Wheat	15.0	13.0	–	–
Soybean meal	9.2	10.3	–	–
Croquelin®[b]	–	5.9		
Fibre-based concentrate[c]	–	–	53.3	–
Starch-lipid-based concentrate[c]	–	–	–	58.7
Others	2.1	2.6	7.9	8.5
Animal outputs	St-SM	O3-SML	St-FC	O3-SCL
	Number of animal-kg live weight per animal			
Breeding bull	1–990	1–990	1–990	1–990
Finished cull cows	16–798	16–802	16–798	16–802
Finished heifers	14–695	14–701	14–695	14–701
Fattened bulls	30–720	30–720	30–720	30–720

St: Standard suckler cow-calf herd with finishing heifers.
O3: Suckler cow-calf herd with finishing heifers enriched in omega-3 FAs through pasture and wrapped grass silage.
SM: Standard bull-fattening herd using a diet rich in starch based on maize silage.
SML: Bull-fattening herd using a diet rich in starch (based on maize silage) supplemented with linseeds.
FC: Bull-fattening herd using a fibre-based concentrate diet.
SCL: Bull-fattening herd using a starch-based concentrate supplemented with linseeds.
[a] Mix meal composition: 30% soybean meal, 40% rapeseed meal and 30% sunflower meal.
[b] Croquelin®: An extruded mix of 50% linseed, 30% wheat bran and 20% sunflower meal.
[c] See composition in Table S2 of Supplementary materials.

The other two diets are high in concentrates, and have been chosen because they represent two different options. One of them (FC) is rich in fibrous by-products; the interest is to use less cereals (which can feed humans) and to minimise the risk of digestive health problems such as acidosis. The other one (SML) is rich in cereals, and maximises the net energy value of the diet, by addition of lipids. The FC herd is located in the Champagne-Ardenne region (northern France), where cattle are frequently fed beet pulp and dehydrated lucerne. The diet (DM basis) of the FC herd consists of 13% straw and 87% concentrate including 22% wheat bran, 22% dehydrated lucerne and 21% dehydrated beet pulp (Eugène et al., 2011). We assumed that animals in FC herd are provided 63 MJ/d of net energy for growth resulting in an ADG of 1.62 kg/d (unpublished experimental data, Mialon M.M., pers. comm.). The SCL herd is located in the Aquitaine region (south-western France), where high-concentrate diets based on cereals are frequently used to fatten bulls. The SCL diet (DM basis) consists of 13% barley straw and 87% concentrate rich in starch and lipids that includes 46% cereals and 6% extruded linseed (Eugène et al., 2011) that provided 62 MJ/d of net energy for growth resulting in an ADG of 1.71 kg/d (unpublished experimental data, Mialon M.M., pers. comm.).

The carcass yields of breeding bulls, finished heifers and finished cull cows were 57%, 56% and 54%, respectively, according to expert knowledge and the slaughterhouse database of the INRA/Vet Agro Sup Herbivore Research Unit. The carcass yield of fattened bulls was 59% according to Institut de l'Elevage (2011) and expert knowledge. All cereals produced on farms with cow-calf herds are consumed on the farm by the herd. Annual ration plans for cow-calf herds and bull-fattening herds and animal outputs of the four systems are presented in Table 1 and in supporting information Table S1 and Table S2.

2.2.2. System boundary and delimitations

This is a cradle-to-farm-gate study for a one-year period, i.e. the studied system includes the production and delivery of inputs used for grassland and cereals produced on-farm, of feed produced off-farm, herd management and associated upstream processes, emissions from the animals and manure storage. The application of manure for cereals and pasture is included, as are buildings. The transport and slaughter of animals leaving the system are not included. Veterinary medicines are not included because of lack of data.

2.2.3. Functional unit and allocation of co-products

The functional units were 1 kg of carcass mass at the farm exit gate for the whole systems, 1 kg live weight gain for each herd and 1 ha of land occupied (both for the whole system and each herd). Carcass mass produced was calculated by multiplying animal live weight at the farm gate by the specific carcass yields for each animal type. Economic allocation was used for feed ingredients resulting from processes yielding several co-products. Allocation was applied for animals

Table 2
Outputs from two reproduction components of Standard and Omega-3 FA-enriched suckler cow-calf herds with finishing heifers and allocation factors following different allocation techniques.

	Standard suckler cow-calf herds with finishing heifers					Omega-3 FA-enriched suckler cow-calf herds with finishing heifers				
	Breeding bull	Cull cow	Weaned female calf	Weaned male calf	Grassland	Breeding bull	Cull cow	Weaned female calf	Weaned male calf	Grassland
Number of animals or grassland area (ha)	1	16	14	30	82	1	16	14	30	81
Live weight mass of animals (kg)	990	690	300	350	–	990	690	300	350	–
Average price of animal products 2004–2007 (€/kg of live weight) or grassland subsidy (€/ha of grassland)	1.3	1.7	2.2	2.6	70	1.3	1.7	2.2	2.6	70
Protein content in live weight mass (g/kg)	75	125	181	181	–	75	125	181	181	–
Allocation factors										
Mass allocation (%)	4	41	16	39	–	4	41	16	39	–
Allocation based on protein content (%)	2	33	19	46	–	2	33	19	46	–
Economic allocation between animal products (%)	2	32	18	48	–	2	32	18	48	–
Economic allocation between animal products and grassland subsidy (%)	2	29	16	44	9	2	29	16	44	9

delivered from the reproduction component of the cow-calf herd (a breeding bull, cull cows, weaned female calves not used for replacement and weaned male calves). We compared different methods for the allocation of impacts to co-products:

1. Allocation on live weight mass. This implies that there is no difference in quality between live weight mass of different animal types. All live weight mass delivered from the reproduction component carried the same environmental burden.
2. Allocation based on protein mass. This was based on the protein content in the live weight mass (CORPEN, 2001) of each co-product delivered from the reproduction component of cow-calf herd.
3. Economic allocation. This was based on the market value of the live weight mass of each co-product delivered from the reproduction component. The prices per kg of live weight mass for each co-product were based on data from the French Livestock Institute for the 2004–2007 period (Réseaux d'élevage Charolais, 2004, 2005, 2006, 2007).
4. Economic allocation with agro-environmental subsidies. Agricultural activity, and in particular grassland-based production systems, has multiple functions such as food production, renewable natural-resource management, landscape and biodiversity conservation and contribution to the socio-economic viability of rural areas (Renting et al., 2009). The agro-environmental measures of the European Union's Common Agricultural Policy (CAP) encourage farmers to maintain the environmental functions of agriculture. Thus, we attributed the environmental impacts of the studied system to these two functions. We used economic allocation based on beef product income as specified above and on agro-environmental subsidies for grassland according to the "Second Pillar" of the 2003 CAP reform in French conditions, to attribute environmental impacts to beef products (per kg of live weight mass) and to environmental services (per hectare of grassland). Subsidies or financial incentives vary between EU countries, and with time, therefore this calculation should be considered as an example for taking into account the effect of public policies on the environmental impact. Allocation techniques are summarised in Table 2.

2.3. Life cycle inventory analysis

2.3.1. Feed production

The cropping and grassland area was determined from total annual feed requirements for the beef production systems and the 4-year (2004–2007) average yields of pasture and crops based on the data of AGRESTE (2009). Grassland management was modelled on grassland production, the stocking rate of the production system and the amount of forage DM required for cattle in winter. The grassland area consisted of 88% permanent and 12% temporary pastures (AGRESTE, 2009). We assumed that permanent grassland did not require tilling and sowing operations. Permanent grassland had a yield of 5.6 t DM/ha/year, 23% of which was harvested as conserved forage (hay and/or wrapped grass silage). Temporary grassland had a higher yield (8.3 t DM/ha/year, 75% was harvested as conserved forage) and was renewed every 5 years by tillage and seeding. Grass not harvested as conserved forage was available for ingestion by animals during grazing. For several reasons (selective grazing, trampling of grass, unfavourable weather conditions) a part of the grass grown is not ingested, this "loss" corresponded to 31.5% of grass dry matter available for grazing. Losses during conservation for both hay and wrapped grass silage were assumed to be 6% of the initial DM. Apart from manure excreted on pasture during grazing, application rates of mineral and organic fertilisers were based on the data of Réseaux d'élevage Charolais (2009) with 1.2 livestock units per ha of forage area as the stocking rate. Pesticide use and other farm practices for grassland (Table S3) were based on a recent survey of agricultural practices (AGRESTE, 2006).

The period considered for crops begins with soil preparation for the specific crop and ends with soil preparation for the next crop. This period may include a catch crop. Data on input use and crop management (Table S3) were based on a recent survey of agricultural practices (AGRESTE, 2006). Data for soybean production (70% soybean from central-western and

Table 3
Estimation of enteric methane (g/kg dry matter intake) produced by different types of animal in different periods in St-SM and St-FC beef-production systems.

	Indoors	Grazing season		
		Late spring	Summer	Autumn
Multiparous cow	22.6	20.0	16.9	15.8
Primiparous cow	22.5	19.3	17.0	16.5
Heifer (>24 months)	21.5	22.3	18.5	–
Heifer (12–24 months)	23.5	19.8	18.1	17.1
Heifer (<12 months)	22.6	–	–	17.5
Breeding bull (>24 months)	21.6	19.1	16.5	15.2
Breeding bull (12–24 months)	23.1	20.9	18.2	17.0
Breeding bull (<12 months)	24.9	–	–	18.6
Pre-finisher	18.7	–	–	–
Cull cow	23.7	–	–	–
Growing heifer	–	–	18.7	17.6
Fattening bull with maize silage	25.1	–	–	–
Fattening bull with fibre-rich concentrate	20.3	–	–	–

St: Standard suckler cow-calf herd with finishing heifers.
SM: Standard bull-fattening herd using a diet rich in starch based on maize silage.
FC: Bull-fattening herd using a fibre-based concentrate diet

30% from southern Brazil) and transport in Brazil was based on Prudêncio da Silva et al. (2010).

2.3.2. Major feed ingredient production

We considered that the transformation of soybean into soybean meal and oil occurred in Brazil based on data by Jungbluth et al. (2007) and Nemecek and Kägi (2007). According to the main French producer of extruded linseeds (Valorex, pers. comm.), the extrusion process required 60 kWh of electricity and 0.21 kWh of natural gas to produce 1 t of Croquelin®. According to information provided by a French dehydration cooperative (Coop de France Déshydratation, pers. comm.), dehydration of lucerne and beet pulp from 25% to 90% DM required 6 GJ/t (mainly supplied by hard coal coke (59%), natural gas (27%) and light fuel oil (10%)) of dehydrated product. Delivery of feed ingredients to the farm and feed mill and the delivery of concentrate feed to the farm were included. We assumed that the fibre-rich concentrate was produced in the Champagne-Ardenne region and starch and lipid-rich concentrate in the Aquitaine region.

2.3.3. Buildings and operations

This study included the production and transportation of materials required for the construction of buildings such as cattle housing, forage and manure storage based on the GES'TIM guide (Gac et al., 2010a). It was assumed that the cattle housing and manure storage had a 30-year life span and that the forage storage had a 50-year life span. However, energy use and emissions during the construction or disposal of the building were not included because of lack of information. The use of machines and energy for housing illumination, feeding, mulching, carrying manure out of housing and cleaning were included as farming operations, based on data from Dollé and Duyck (2007).

2.3.4. Emissions and effect of land use and land-use change (LULUC) on soil C balance

Enteric CH_4 emissions were estimated for each class of cattle according to the method developed by Vermorel et al. (2008) for cattle production in France and used for French gaseous-emissions inventories. This method uses animals' net-energy requirements, converted into metabolisable energy intake (MEI), and conversion factors from MEI to methane energy (Y'm = MJ CH_4/100 MJ MEI), to express CH_4 emissions per kg of DM intake (DMI). This allowed the consideration of diet characteristics for each class of cattle (Table 3). This method is not applicable to diets rich in lipids. To include the effect of diets supplemented with lipids rich in omega-3 FAs on ruminants' enteric methane production, a 4.8% reduction factor of enteric methane production (g CH_4/kg DMI) per percentage unit of added lipids was applied, based on results from a quantitative analysis (Martin et al., 2010).

The cow-calf herd was housed in deep bedding from December to April (4.5 months). The manure accumulated indoors was removed once a year. For bull-fattening herds, it was assumed that cattle remained indoors during the fattening period and that slurry was evacuated and stored outside the animal housing without a natural crust cover. Methane, nitrous oxide and ammonia emissions from manure produced by cattle in housing and during storage were included as part of livestock manure management, and emissions from manure deposited during grazing were included as part of grassland production. Nitrogen excretion was calculated as the difference between the animal's total nitrogen intake in feed and the nitrogen retained for growth (meat production) for each grazing and indoor period. For P-excreted on pasture, our estimation was based on Corpen (2001) taking into account the number of livestock units and the duration of grazing per ha of grassland. A summary of emission factors used for livestock, cropping and grassland production and their sources is presented in Table 4.

The effect of land use on C sequestration in grassland was estimated according to Dollé et al. (2009) from measurements of C in soils summarised by Arrouays et al. (2002). For permanent grassland, i.e. grasslands older than 30 years, C sequestration was estimated at 200 kg C/ha/year. We assumed that temporary grassland was maintained for 5 years and was followed by an annual crop for 2 years. C sequestration was assumed to equal 500 kg C/ha of temporary grassland/year and C release during the subsequent 2 years of annual crops was estimated at 1000 kg C/ha/year. As a result, there is a net C sequestration for temporary grassland of 100 kg C/ha/year. We assumed that

Table 4
Emissions sources, equation or emission factor used and reference.

Pollutant/source		Equation/emission factor	Reference
Manure management			
Direct N_2O	$= \text{N excreted (kg)} \times \text{EF}^{a} \times 44/28$		IPCC (2006) Tier 2
	Deep bedding manure	EF = 0.07 kg N_2O–N/kg N	
	Slurry without natural crust cover	EF = 0 kg N_2O–N/kg N	
Indirect N_2O	$= \text{N excreted (kg)} \times \text{Frac}_{\text{Gas}}{}^{b}\ (\%) \times 0.01 \times 44/28$		IPCC (2006) Tier 2
	Deep bedding manure	$\text{Frac}_{\text{Gas}} = 30\%$	
	Slurry without natural crust cover	$\text{Frac}_{\text{Gas}} = 40\%$	
CH_4	$= [[\text{GEI}^{c} \times (1 - \text{DE}^{d}\%)/100 + \text{UE*GEI}^{e}] \times 0.92)/18.45] \times 0.17 \times 0.67 \times \text{MCF}^{f}\ (\%)/100$		IPCC (2006) Tier 2
	Deep bedding manure	UE = 0.04; MCF = 4	
	Slurry without natural crust cover	UE = 0.04 for SM and SML and 0.02 for SCL and FC; MCF = 27%	
NH_3	In housing	$= 0.12 \times \text{N excreted (kg)} \times 17/14$	Payraudeau et al. (2007)
	In storage	$= 0.06 \times \text{N remaining (kg)} \times 17/14$	
Cropping and grassland production			
Direct N_2O	$= [[\text{(mineral N (kg)} + \text{liquid N (kg)} + \text{cattle manure N (kg)} + \text{residue N (kg)}] \times 0.01 + \text{N deposited by grazing} \times 0.02)] \times 44/28$		IPCC (2006) Tier 2
Indirect N_2O	$= [[[\text{(mineral N (kg)} + \text{liquid N (kg)}] \times 0.1 + \text{cattle manure N (kg)} \times 0.2] \times 0.01 + \text{N–NO}_3\ \text{(kg)} \times 0.0075] \times 44/28$		IPCC (2006) Tier 2
NO_x	$= 0.21 \times N_2O$ (kg)		Nemecek and Kägi (2007)
NH_3	$= (0.02 \times \text{mineral N (kg)} + 0.08 \times \text{liquid N (kg)} + 0.076 \times \text{cattle manure N (kg)} + 0.08 \times \text{N deposited by grazing)} \times 17/14$		Nemecek and Kägi (2007); Payraudeau et al. (2007); CORPEN (2006)
NO_3	Cropping	See values in Table S3	Basset-Mens et al. (2007)
	Grassland	$= 8.77\ e^{0.003 \times \text{grazing days/ha/LU}^{g}} \times 62/14$	Vertès et al. (1997)
P leaching	Cropping	= 0.07 kg P/(ha × year)	Nemecek and Kägi (2007)
	Grassland	= 0.06 kg P/(ha × year)	
P run-off	$= \text{P run-off lost} \times [1 + 0.2/80 \times \text{mineral } P_2O_5 \text{ (kg)} + 0.4/80 \times \text{manure } P_2O_5 \text{ (kg)} + 0.7/80 \times P_2O_5 \text{ deposited by grazing (kg)}]$		Nemecek and Kägi (2007)
	Cropping	P run-off lost = 0.175 kg P/(ha × year)	
	Grassland	P run-off lost = 0.15 kg P/(ha × year)	
P erosion	$= 10{,}000 \times (80 \times 0.033 \times 0.38 \times 0.65 \times \text{effect of the vegetation cover factor}) \times 0.00095 \times 1.86 \times 0.2$ kg P/(ha × year)		Nemecek and Kägi (2007) and Nemecek et al. (2003)

[a] EF: emission factor for direct N_2O emissions from manure management.
[b] Frac_{Gac}: % of managed manure nitrogen for production system that volatilises as NH_3 and NO_x.
[c] GEI: gross energy intake.
[d] DE: digestibility of the feed.
[e] UE × GEI: urinary energy expressed as fraction of GEI.
[f] MCF: methane conversion factor from each manure-management system (in %).
[g] LU: livestock unit.

other annual crop area was converted from permanent grassland more than 20 years ago and that agricultural practices for these crops had no effect on soil carbon. The part of Brazilian forest converted to soybean was estimated based on Prudêncio da Silva et al. (2010). In order to better conform to current practice with respect to the effect of land-use change on C release due to conversion of Brazilian forest to cropland we decided to adopt a value of 740 t CO_2/ha as recommended in PAS 2050 (2008) among others, instead of the value of 120 t CO_2/ha used in the Ecoinvent database (Jungbluth et al., 2007).

2.4. Life cycle impact assessment

The impact categories considered were climate change (CC), eutrophication potential (EP), acidification potential (AP), cumulative energy demand (CED) and land occupation (LO). The indicator value for each impact category was determined by multiplying the aggregated resources used and the aggregated emissions of each individual substance with a characterisation factor for each impact category to which it may potentially contribute, as implemented in the Ecoinvent® v2.0 database. CC is defined as the potential impact of gaseous emissions on the heat radiation absorption in the atmosphere. It was calculated according to the 100-year global warming potential factors in kg CO_2 equivalent (eq), CH_4: 25, N_2O: 298, CO_2: 1 (IPCC, 2007). Climate change does not take into account the effect of LULUC on C sequestration in grassland and C release due to conversion of Brazilian forest to cropland, whereas CC/LULUC takes into account these effects. CED accounts for the use of renewable and non-renewable energy resources by using the conversion efficiencies of primary energy carriers. Eutrophication covers all potential impacts of high environmental levels of macronutrients, in particular N and P. EP was calculated using the generic EP factors in kg PO_4 eq, NH_3: 0.35, NO_3: 0.1, NO_2: 0.13, NO_x: 0.13, PO_4: 1 (Guinée et al., 2002). Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface water, biological organisms, ecosystems and materials. AP was calculated using the average European AP factors in kg SO_2 eq, NH_3: 1.6, NO_2: 0.5, NO_x: 0.5, SO_2: 1.2 (Guinée et al., 2002). Land occupation, including on-farm and off-farm area, refers to the loss of land as a resource in the sense of being temporarily unavailable for other purposes due to crop and grass production.

Table 5
Impacts per kg of carcass mass and per ha of land occupation (both on-farm and off-farm) of the four beef-production systems.

		St-SM	O3-SML	St-FC	O3-SCL	St-SM	O3-SML	St-FC	O3-SCL
		per kg of carcass mass				per ha of land occupation			
Climate change	kg CO_2 eq	27.8	27.7	27.9	27.0	5770	5880	5980	5780
Climate change/LULUC	kg CO_2 eq	25.5	25.5	25.3	24.4	5290	5400	5420	5240
Cumulative energy demand	MJ	64.8	68.4	73.4	71.1	13,470	14,510	15,720	15,260
Eutrophication	kg PO_4^{3-} eq	0.098	0.098	0.094	0.098	20.5	20.9	20.1	21.1
Acidification	kg SO_2 eq	0.169	0.173	0.168	0.173	35.2	36.7	35.9	37.1

St: Standard suckler cow-calf herd with finishing heifers.
O3: Suckler cow-calf herd with finishing heifers enriched in omega-3 FAs through pasture and wrapped grass silage.
SM: Standard bull-fattening herd using a diet rich in starch based on maize silage.
SML: Bull-fattening herd using a diet rich in starch (based on maize silage) supplemented with linseeds.
FC: Bull-fattening herd using a fibre-based concentrate diet.
SCL: Bull-fattening herd using a starch-based concentrate supplemented with linseeds.
LULUC: Land use and land-use change.

3. Results

3.1. Environmental impacts

The environmental impacts of these systems are presented per kg of carcass mass and per ha of land occupied during a year (Table 5). Thus, carcass mass for each system consisted of fattened bulls, but also the corresponding output of the cow-calf herd (i.e. a breeding bull, finished heifers and finished cull cows, see Fig. 1). We observed minor differences between the four systems per kg of carcass mass and per ha (+/−5% relative to St-SM) for all impact categories except CED. The lowest values per kg of carcass mass for CC and CC/LULUC were obtained in O3-SCL. The lowest values for CED were observed in St-SM. The highest CED values were observed in St-FC, with 13 and 17% per kg of carcass mass and per ha, respectively, higher than those for St-SM. Consideration of the effect of LULUC induced a reduction of 9% of the CC impact for both functional units.

In our systems, enteric fermentation was the greatest contributor (39–41%) to CC followed by grassland production (24–25%), emissions from manure management (21–22%), and production of other feed (9–10%). Both building and farming operation only contributed 4% to CC (Fig. 2). The contribution of grassland production to CC/LULUC was lower than it was to CC. For other impact categories, grassland production was the major contributor to the environmental impacts of production systems (58–63% of EP, 46–47% of AP and 81–83% of LO). The production of other feed contributed 19–23% to EP, 12–13% to AP and 14–16% to LO. For CED impact, grassland production, other feed production, building and farming operation contributed approximately a third each. The emissions from manure contributed 17–18% and 37–39% to EP and AP, respectively.

For all scenarios, the cow-calf herd contributed most to the environmental impacts of the beef production system (Fig. 3). The contribution of the cow-calf herd to the impacts per kg of carcass mass was highest for LO (95%), followed by CC (89%), CC/LULUC (87%), EP (88%), AP (85%) and lowest for CED (78%). In general, environmental impacts to produce 1 kg of live weight gain in a bull-fattening herd (SM, SML, FC and SCL) were lower (−35% to −89%, according to the impact category) than those in a cow-calf herd (St and O3), except for CED in FC (+55%) and SCL (−6%) (Table 6). Nevertheless, when the environmental impacts of each herd are expressed per ha (Table S5), the impacts of the bull-fattening herd were 2–5 times higher than those of the cow-calf herd, except for CED of FC (14 times). Comparing St and O3, the impacts expressed per kg of live weight gain and per ha were higher for O3. In comparing the four bull-fattening herds, all impacts expressed per ha and CED per kg of live weight gain of FC were highest.

3.2. Effect of allocation methods on co-product impacts

The systems delivered carcass mass of four types of animals: fattened bulls (50% total carcass mass), finished heifers (21%), finished cull cows (27%) and a breeding bull (2%). The relative impacts of each type of carcass mass in each system varied according to the allocation method used and the impact considered (Table 7 and Table S6). With mass allocation, for all systems studied, impact values for finished cull cows were highest, followed by those for breeding-bull carcass, finished heifers, and fattened bulls, except for CED of fattened bulls in St-FC. With other allocation methods, impact values for breeding-bull carcass were lowest in all systems. Whatever the allocation method used, impact values for fattened-bull carcass were lower than those for finished cull-cow and finished-heifer carcass, except for CED. For finished cull-cow and finished-heifer carcass, protein allocation yielded higher impact values than economic allocation, but for fattened-bull carcass the opposite occurred.

Economic allocation between beef-product income and agro-environmental subsidies resulted in the attribution of approximately 9% of the impacts of the reproduction component of beef-production systems to ecosystem services (Table 2). Impact of activities to maintain ecosystem services, expressed per ha of grassland, is presented in Table S7. The allocation of impacts to ecosystem services reduced impact values per kg of carcass by 6–9% relative to economic allocation without considering ecosystem services.

4. Discussion

4.1. Comparison with previous studies

Previous LCA studies on cradle-to-farm-gate beef-production systems show a large variability between impacts. Climate-change impact of the whole suckler beef-production system, without consideration of LULUC, reported from studies in Brazil (Cederberg et al., 2009), the European Union (Nguyen

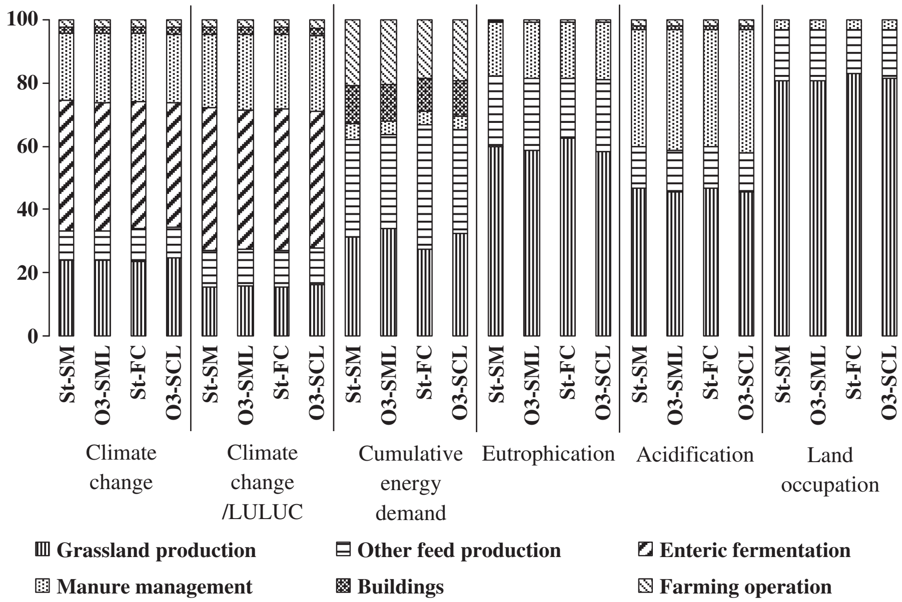

Fig. 2. Contribution (in %) of main components in environmental impacts of the four beef-production systems. St: Standard suckler cow-calf herd with finishing heifers. O3: Suckler cow-calf herd with finishing heifers enriched in omega-3 FAs through pasture and wrapped grass silage. SM: Standard bull-fattening herd using a diet rich in starch based on maize silage. SML: Bull-fattening herd using a diet rich in starch (based on maize silage) supplemented with linseeds. FC: Bull-fattening herd using a fibre-based concentrate diet. SCL: Bull-fattening herd using a starch-based concentrate supplemented with linseeds. LULUC: Land use and land-use change.

et al., 2010), the United Kingdom (Williams et al., 2006) and Canada (Beauchemin et al., 2010) were 28.2, 27.3, 25.3 and 21.7 kg CO_2 eq/kg carcass mass, respectively. Our results (27.0–27.9; Table 5) are within the range obtained by these authors. Expressed per kg of live weight, CC impact varied from 15.3 to 15.9 kg CO_2 eq (data not shown) in our study, and are within the range obtained by Pelletier et al. (2010) in the United States (US; 14.8–19.2 kg CO_2 eq) and by Gac et al. (2010b) and Veysset et al. (2010, 2011) in France (14.1–20.2 kg CO_2 eq). For other impacts, our results per kg of carcass mass represented 38–60% for EP, 24–80% for AP, and 112–125% for LO relative to the impact values obtained by Williams et al. (2006) and Nguyen et al. (2010). Per ha of land occupation, our figures represented 88–92% for CC, 31–55% for EP, and 20–72% for AP relative to the impact values converted from Nguyen et al. (2010) and Williams et al. (2006). Differences between the present study and literature data can be partly explained by differences between production system characteristics. Our cow-calf herds are extensive production systems in which nearly 80% of the surface was permanent grassland. In our systems, cows are 3-years-old at calving and provide an average of 4.3 calvings per lifetime; the more productive US or Canadian systems provide 6.7 and 6.5 calvings/cow, respectively. Another point is that in the system we studied, weaned female calves not used to replace cows are also reared as heifers to replace cows until the age of 29 months and then they are fattened on pasture until 33 months. Only weaned male calves are intensively fattened to produce bulls. In this study, the results for CC/LULUC are based on data for C sequestration in French agricultural soils; they are far below recent data on grassland C sequestration reported by Soussana et al. (2010) for certain European conditions and may underestimate the extent of net C storage in soils. A minor reduction in CC impact (9%) was obtained in this study regardless of the functional unit used. However, Pelletier et al. (2010) estimated a decrease in CC impact of 11% to 43% by considering C sequestration in improved pastures (120 kg C/ha/year) and unmanaged pastures (400 kg C/ha/year) under US conditions, but C loss from arable soils converted from pastures was not included. Higher compensation of CC impact (13–21%) was obtained by Veysset et al. (2011) because C sequestered in permanent grassland was higher (350 kg C/ha), and C release was considered only for the proportion of cropland converted each year from temporary grassland.

For our systems, the relative contribution of the cow-calf herds to overall impacts was higher than for those reported by Pelletier et al. (2010). This is partially due to the higher replacement rate of cows in our systems and to the bull-fattening herd, which concerned only weaned male calves. These results suggest that research emphasis should be put on the cow-calf herds to reduce the environmental impacts of this beef-production system. When the cow-calf herds and the bull-fattening herd are considered separately, the former uses much more land to produce 1 kg of live weight gain than the latter. However, these cow-calf herds were located on extensive grasslands in the Massif Central region with a low potential for annual crop production. Beef-cattle farming in this region, principally based on permanent grassland, plays an important role in sustaining the rural population and an attractive countryside. This is demonstrated by the low environmental impacts per ha of land for the cow-calf herds, which represented 19–55% of those for the bull-fattening herd, except for CED of St vs. FC (7%). Our values for CC per kg of live weight gain for the bull-fattening herd were higher than those reported for a feedlot finishing phase by Phetteplace et al. (2001) in the United States and Doreau et al. (2011b) in France

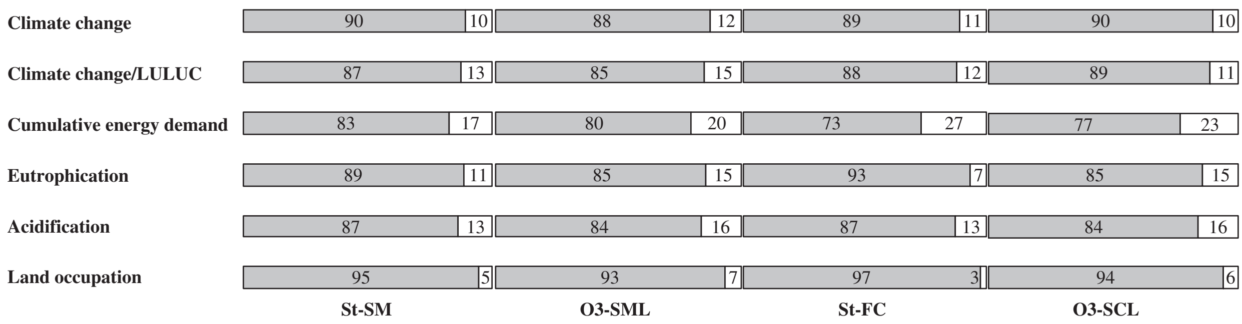

Fig. 3. Contribution (%) of suckler cow-calf herd with finishing heifers (grey boxes) and of bull-fattening herd (white boxes) to the environmental impacts of the four beef-production systems. St: Standard suckler cow-calf herd with finishing heifers. O3: Suckler cow-calf herd with finishing heifers enriched in omega-3 FAs through pasture and wrapped grass silage. SM: Standard bull-fattening herd using a diet rich in starch based on maize silage. SML: Bull-fattening herd using a diet rich in starch (based on maize silage) supplemented with linseeds. FC: Bull-fattening herd using a fibre-based concentrate diet. SCL: Bull-fattening herd using a starch-based concentrate supplemented with linseeds. LULUC: Land use and land-use change.

but lower than those of Ogino et al. (2004) in Japanese conditions.

4.2. Effect of omega-3 FA enrichment in the diet and of the proportion of concentrate on environmental impacts

Both per kg of carcass mass and per ha of land occupation, minor differences between the four systems were observed for CC, EP and AP. This can be explained by the high contribution of the cow-calf herd (Fig. 2) on the environmental impacts of these systems and the minor differences between St and O3 (Tables 6 and S5). The production strategy (indoor finishing of cull cows and outdoor finishing of heifers not used for replacement) and the technical characteristics (grassland yield per ha, livestock units per ha of grassland, annual calving rate and replacement rate) were similar for these two cow-calf herds. The differences in the calving period (February or January), the age at which the male calf was sent to the fattening system (11 or 9 months) and the use of forage in winter (only hay or wrapped grass silage and hay) did not greatly differentiate the environmental impacts of St and O3 herds. Apart from replacing hay with wrapped grass silage, there is no other simple and economically viable means to increase omega-3 FAs, as in the suckler cow-calf herds with finishing heifers only a small amount of concentrate is fed to each animal. Among forages, differences in omega-3 FA content are mainly related to the mode of conservation and the age at cutting, and depend to a lesser extent on forage species (Van Ranst et al., 2009).

Differences between systems are larger when the bull-fattening herd is considered alone. The use of rations with 87% concentrate for animals in FC and SCL herds increased CED both per kg of live weight gain and per ha, due to feed-ingredient production and feed processing, compared to the use of rations based on maize silage for animals in SM and SML herds. In the bull-fattening herd, CC was lower with a concentrate diet based on starch (SCL) than with a forage diet based on maize silage (SML) via the strong reduction of enteric methane related to a high proportion of concentrate and a higher-than-average daily gain for bulls. It is known that an increase in proportion of concentrate in the diet decreases enteric methane emissions from ruminants (Martin et al., 2010). Doreau et al. (2011b) reported that a strong decrease in enteric methane emissions of fattening bulls fed with an 86% concentrate diet based on maize grain induced a reduction of CC during the fattening phase compared to using a forage diet based on maize silage. However, a reduction of enteric methane produced by bulls fed with a concentrate diet based on fibre (FC) compared to bulls fed with a diet based on maize silage was countered by higher emissions of nitrous oxide and carbon dioxide from dehydration of beet pulp and lucerne. A minor reduction of CC, CED, AP and LO expressed per kg of live weight gain was obtained in SML compared to SM. Feeding a starch concentrate supplemented with extruded linseed (SCL) strongly reduced CC compared to that obtained in FC via a high reduction of enteric methane and a higher average daily gain for bulls in SCL and a higher carbon dioxide emission in FC due to dehydration of beet pulp and lucerne (Table S4). The SCL feeding strategy had higher EP impact per kg of live weight gain than the FC strategy, due to low nitrate emissions from the production of a fibre-rich concentrate compared to that of a concentrate rich in starch and lipids and a higher yield of lucerne and beet pulp compared to cereals. The high increase in CED of FC resulted from the energy required for lucerne and beet pulp dehydration to produce the fibre-rich concentrate. The impacts of the FC diet may have resulted more from current industrial processes of feedstuffs than from their chemical composition. It should be noted that the fibre-rich concentrate contained 75% co-products (wheat bran, dehydrated beet pulp, wheat middlings, etc.) which can be digested by ruminants and thus avoid feed competition with other livestock and humans.

4.3. Effect of allocation methods on co-product impacts

The choice of allocation methodology for handling the co-products has a decisive effect on LCA results (Cederberg and Stadig, 2003) and is still under debate. Beef-production systems produce four types of animals (fattened bulls, finished heifers, finished cull cows and a breeding bull) which differ not only in production methods but also in economic value and protein content of live weight mass. The question raised was how to determine the environmental impacts of each type of animal in each system. To our knowledge, no published LCA study has yet examined the environmental impacts of different types of animals produced in a beef-production system. According to the ISO recommendation, allocation should

Table 6
Impacts per kg of live weight gain produced of two suckler cow-calf herds with finishing heifers and four bull-fattening herds.

		Suckler cow-calf herd with finishing heifers		Bull-fattening herd			
		St	O3	SM	SML	FC	SCL
Climate change	kg CO_2 eq	17.5	18.3	8.6	8.0	9.1	6.3
Climate change/LULUC	kg CO_2 eq	15.7	16.3	9.5	8.8	9.1	6.4
Cumulative energy demand	MJ	37.8	41.0	33.1	32.3	58.5	38.7
Eutrophication	g PO_4^{3-} eq	62	63	32	33	19	33
Acidification	g SO_2 eq	103	109	67	65	63	65
Land occupation	m^2year	32.1	33.1	7.8	7.4	3.6	6.3

St: Standard suckler cow-calf herd with finishing heifers.
O3: Suckler cow-calf herd with finishing heifers enriched in omega-3 FAs through pasture and wrapped grass silage.
SM: Standard bull-fattening herd using a diet rich in starch based on maize silage.
SML: Bull-fattening herd using a diet rich in starch (based on maize silage) supplemented with linseeds.
FC: Bull-fattening herd using a fibre-based concentrate diet.
SCL: Bull-fattening herd using a starch-based concentrate supplemented with linseeds.
LULUC: Land use and land-use change.

be avoided whenever possible by dividing the main process into sub-processes or by expanding the production system to include additional functions related to the co-products (ISO, 2006). Where allocation cannot be avoided, the allocation should be performed by determining physical causal relationships (JRC, 2010) or the market value of the co-products. For dairy-production systems, biological and economic allocation have often been used to allocate impacts of milk and meat products than mass allocation (Yan et al., 2011) and protein allocation, although ISO standards prefer mass and protein allocation to economic allocation. In fact, allocation based on biological rules reflects a physical causal relationship and is recommended first among other physical causalities such as mass and protein. Protein allocation allows comparison of animal products through protein content (de Vries and de Boer, 2009) and reflects that a main function of the beef-production sector is to provide humans with edible protein. In LCA studies, economic allocation is the most common method (de Vries and de Boer, 2009) because products are manufactured corresponding to a demand reflected in their market value (Jolliet et al., 2010).

We therefore analysed the effects of mass, protein and economic allocation on the impacts of four types of animals produced in each system. The allocation approach strongly affected the impacts per kg of carcass mass of breeding bull and, to a much lesser extent, of finished cull cows, fattened bulls and finished heifers. This is because the live weight mass of a breeding bull has lower protein content and economic value than that of the other animal types. The difference in impacts was lowest between protein and economic allocation for fattened bulls, finished cull cows and the breeding bull, and was lowest between mass and economic allocation for finished heifers. Economic allocation could thus be considered a reference allocation method in beef systems.

Table 7
Climate-change impacts and cumulative energy demand per kg of carcass mass of four types of animals delivered from the four production systems according to four allocation methods.

	Fattened bull				Finished heifer		Finished cull cow		Breeding bull	
	St-SM	O3-SML	St-FC	O3-SCL	St	O3	St	O3	St	O3
Climate-change (kg CO_2 eq)										
Mass allocation	22.4	22.1	22.8	20.6	31.0	31.2	34.8	34.9	31.9	32.2
Protein allocation	25.0	24.7	25.4	23.2	33.6	33.8	29.2	29.3	15.5	15.6
Economic allocation	25.9	25.6	26.3	24.1	31.9	32.1	28.6	28.6	19.6	19.9
Economic allocation with subsidies	24.2	24.0	24.5	22.5	28.8	29.1	26.3	26.4	17.8	18.1
Cumulative energy demand (MJ)										
Mass allocation	59.1	62.7	76.5	68.3	63.5	66.9	76.0	79.5	69.3	73.7
Protein allocation	64.8	68.7	82.2	74.3	69.1	72.9	63.9	66.8	33.7	35.8
Economic allocation	66.7	70.8	84.1	76.4	65.5	69.1	62.5	65.2	42.7	45.4
Economic allocation with subsidies	63.0	67.0	80.4	72.5	59.3	62.5	57.5	60.1	38.8	41.4

St: Standard suckler cow-calf herd with finishing heifers.
O3: Suckler cow-calf herd with finishing heifers enriched in omega-3 FAs through pasture and wrapped grass silage.
SM: Standard bull-fattening herd using a diet rich in starch based on maize silage.
SML: Bull-fattening herd using a diet rich in starch (based on maize silage) supplemented with linseeds.
FC: Bull-fattening herd using a fibre-based concentrate diet.
SCL: Bull-fattening herd using a starch-based concentrate supplemented with linseeds.
Beef-production systems: 1) St-SM, 2) O3-SML, 3) St-FC, and 4) O3-SCL.

The process of CAP reforms has reoriented the development of agriculture in Europe towards the principles of rural development and agricultural multifunctionality (Daniel and Perraud, 2009). The “Second Pillar” of the CAP focuses on agro-environmental subsidies. These subsidies are intended for landscape management, nature conservation, environmental protection, biodiversity and rural development and concretely reflect social demand toward maintaining grassland with a low stocking rate. LCA has been criticised for considering only “negative” impacts and excluding the positive impacts of agriculture (e.g. Bockstaller et al., 2010). We do believe that this multifunctionality of agriculture, including the provision of ecosystem services, can be included simply by considering such services as co-products. We therefore allocated the impacts of the systems to both their production function (expressed in animal products) and the provision of environmental services (expressed in grassland area). This method resulted in attribution of 9% of the environmental impacts of the reproduction component of beef-production systems to the activities for maintaining ecosystem services. Frequent modifications of CAP reforms result in the adaptation of farming practices to maximise the subsidies (Bélard and Liénard, 2001). Clearly, a modification in agro-environmental subsidies for grassland reflects a modification in social demand regarding the contribution of grasslands on public goods such as biodiversity and landscapes. The allocation of impacts to animal products and to the activities for maintaining ecosystem services will be modified according to the policy adopted. This approach is an initial attempt to consider the ecosystem services provided by farming systems as co-products when estimating the environmental impacts of animal production. A comparable approach has been suggested for Spanish sheep farming systems (Ripoll-Bosch et al., 2011).

5. Conclusions

Our cradle-to-farm-gate study shows that most environmental impacts of beef-production systems emanate from the suckler cow-calf herd with finishing heifers. As a result of the considerable contribution of this herd to the entire system's impacts and the small differences between the standard and omega-3 FA-enriched herds, the environmental impacts of the four investigated systems did not clearly differ, even though those of the bull-fattening herds varied widely. Including effect of land use and land-use change induced a reduction of 9% of climate-change impacts for the entire production system. Use of linseed for the bull-fattening herd did not influence the systems' environmental impacts. This study further revealed that more research for mitigation of the environmental impacts of beef production should focus on the suckler cow-calf herd with finishing heifers.

The allocation approach strongly affected the impacts per kg of carcass mass of a breeding bull and finished cull cows and, to a much lesser extent, those of fattened bulls and finished heifers. The application of economic allocation considering agro-environmental subsidies has shown that the environmental services of farming systems can be considered in LCA studies, which thus can include the positive impacts of farming systems, such as landscape management and biodiversity conservation. This concept needs to be discussed and developed to highlight and preserve the environmentally friendly aspects of farming systems.

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Conflict of interest

We do not have any actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

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Effects of type of ration and allocation methods on the environmental impacts of beef-production systems

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Supplementary materials

Table S1: Description of animal categories, duration in pasture and in housing, and annual ration plan for the Standard (St) and enriched omega-3 FA (O3) suckler cow-calf herds with finishing heifers

Type and number of animal		Duration in pasture (d)		Duration in housing (d)		Annual ration per animal category (t DM)											
						Grazed grass		Hay		Wrapped grass silage		Barley grain		Wheat grain		Mix meal[3]	
		St	O3	St	O3	St	O3	St	O3	St	O3	St	O3	St	O3	St	O3
Cows	70	228	228	137	137	199	191	103	53.5	-	49.2	11.9	14.0	12.3	14.2	0.3	0.2
Heifers (>24 mo)	30	76	46	76	106	8.8	4.2	16.1	10.3	-	10.3	1.1	1.5	1.3	1.5	0.2	-
Heifers (12-24 mo)[1]	31	228	228	137	137	43.6	45.7	21.2	13.0	-	12.8	3.5	2.1	3.7	2.1	0.3	-
Heifers (<12 mo)	31	31	61	61	31	3.8	7.6	9.8	2.1	-	2.2	1.6	1.9	1.8	1.9	-	-
Breeding bulls (>24 mo)	3	228	228	137	137	6.2	5.8	6.7	3.4	-	3.8	0.4	0.4	0.6	0.4	0.04	-
Breeding bull (<24 mo)	1	228	228	137	137	2.2	2.6	1.4	0.5	-	0.5	0.4	0.3	0.4	0.3	0.04	-
Calves[2]	62	198	168	76	106	-	-	-	-	-	-	4.5	4.2	10.2	9.3	4.5	4.2
Male pre-finishers	30	-	-	61	-	-	-	3.8	-	-	-	4.2	-	4.2	-	1.3	-
Cull cows	16	-	-	102	102	-	-	13.2	0	-	13.0	5.4	5.0	5.4	5.1	-	-
Growing heifers	14	122	122	0	0	12.8	13.7	-	-	-	-	1.7	1.3	1.6	1.3	-	-

[1]one heifer died

[2]one weaned male calf replaced the breeding bull

[3]Mix meal composition: 30% soybean meal, 40% rapeseed meal and 30% sunflower meal

Table S2: Composition (in %) of fibre-based concentrate (90.2% DM) and starch-lipid-based concentrate (88.5% DM)

	Fibre-based concentrate	Starch-lipid-based concentrate
Wheat	-	8.6
Barley	2.5	9.7
Maize		28.0
Dehydrated beet pulp	21.5	6.0
Dehydrated lucerne	22.5	-
Wheat bran	28.0	-
Wheat middlings	12.5	3.0
Soybean meal	-	2.0
Rape seed meal	3.5	21.4
Croquelin®	-	12.0
Other raw materials	7.3	8.0
Mineral	2.2	1.3

DM: Dry matter

Croquelin® composition: 50% extruded linseed, 30% wheat bran and 20% sunflower meal

Table S3: Main inputs used, dry matter yield and nitrate-N emitted for pastures and the major feed crops[1]

Pasture or crop type	N mineral	N manure	P_2O_5 (triple superphos phate)	K_2O (potassium chloride)	CaO	Seed	Pesticide (active ingredient)	Diesel	Agricultural machinery	Irrigation water	Plastic for wrapped silage	Yield (dry matter)[2]	Nitrate-N emitted
	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	m^3/ha	kg/ha	kg/ha	kg/ha
Permanent grassland for St	28	27	19	39	167	0	0	30	5	0	0	5640	20
Temporary grassland for St	33	0	28	58	167	6	0	51	13	0	0	8280	20
Permanent grassland for O3	28	27	19	39	167	0	0	29	5	0	7	5640	20
Temporary grassland for O3	33	0	28	58	167	6	0	50	14	0	12	8280	20
Wheat	171	7	37	24	167	140	2.6	99	23	0	0	5650	40
Barley	129	6	37	26	167	125	2.6	100	24	0	0	5550	40
Silage maize	57	138	31	29	167	20	1.0	91	22	354	16	11000	40
Soybean from Brazil	6	1	80	80	518	53	1.7	76	18	0	0	2708	18
Linseed	70	0	45	25	0	46	0.8	90	22	0	0	1800	40
Sugar beet	103	32	68	146	167	2	3.4	97	22	99	0	18070	40
Lucerne	0	0	119	256	333	8	0.9	73	19	0	0	13970	15

St: Standard suckler cow-calf herd with finishing heifers

O3: Suckler cow-calf herd with finishing heifers enriched in omega-3 FAs through pasture and wrapped silage

[1]Data for grassland and all crops concern a one-year period, except for soybean, where data are for a six-month period

[2]Yield of grassland corresponds to the yield obtained when all grass is machine harvested. 23% and 75% of the yield of permanent and temporary grassland, respectively, was machine harvested as conserved forage (hay and/or wrapped grass silage). Losses during conservation for both hay and wrapped grass silage were assumed to be 6% of the initial DM. Grass not harvested as conserved forage was available for ingestion by animals during grazing. For several reasons (selective grazing, trampling of grass, unfavourable weather conditions) a part of the grass grown is not ingested, this “loss” corresponded to 31.5% of grass dry matter available for grazing.

Table S4: Environmental impacts due to the production of 1 t of forages[1] and other feed ingredients

	Unit	Climate change kg CO_2 eq	Climate change/LULUC kg CO_2 eq	Cumulative energy demand MJ	Eutrophication kg PO_4^{3-}eq	Acidification kg SO_2 eq	Land occupation ha*a
Hay from St permanent grassland	t DM	365	227	1531	3.0	4.3	0.189
Grazed grass from St permanent grassland	t DM	433	243	1017	4.0	5.5	0.259
Hay from St temporary grassland	t DM	198	151	1098	1.7	1.5	0.129
Grazed grass from St temporary grassland	t DM	231	167	863	2.3	1.9	0.177
Hay from O3 permanent grassland	t DM	367	229	1509	3.0	4.3	0.189
Wrapped silage from O3 permanent grassland	t DM	405	267	2771	3.0	4.5	0.189
Grazed grass from O3 permanent grassland	t DM	438	248	1017	4.0	5.6	0.259
Hay from O3 temporary grassland	t DM	199	152	1085	1.7	1.5	0.129
Wrapped silage from O3 temporary grassland	t DM	214	167	1575	1.7	1.6	0.129
Grazed grass from O3 temporary grassland	t DM	234	170	862	2.3	1.9	0.177
Wheat	t DM	551	551	3507	4.5	4.9	0.163
Barley	t DM	475	475	3208	4.2	4.0	0.166
Maize silage	t DM	279	279	1644	2.6	2.6	0.092
Starch-lipid-based concentrate[2]	t DM	587	606	6344	4.9	4.3	0.128
Fibre-based concentrate[2]	t DM	685	686	9454	2.4	4.0	0.109
Mix meals[3]	t DM	566	851	7416	5.0	4.6	0.167
Dehydrated lucerne	t DM	961	961	14660	1.2	4.5	0.074
Dehydrated beet pulp	t DM	902	902	14430	0.6	4.7	0.012
Croquelin®	t DM	686	686	6461	9.0	5.3	0.177

St: Standard suckler cow-calf herd with finishing heifers

O3: Suckler cow-calf herd with finishing heifers enriched in omega-3 FAs through pasture and wrapped silage

DM: dry matter

SCL: Bull-fattening herd using a starch-based concentrate supplemented with linseed

FC: Bull-fattening herd using a fibre-based concentrate diet

[1]Impacts correspond to ingested forages and grazed grass from grassland

[2]See composition in Table S3

[3]Mix meal composition**:** 30% soybean meal, 40% rapeseed meal and 30% sunflower meal

Croquelin® composition: 50% extruded linseed, 30% wheat bran and 20% sunflower meal

Table S5: Impacts per ha of two suckler cow-calf herds with finishing heifers and four bull-fattening herds

		suckler cow-calf herd with finishing heifers		Bull-fattening herd			
		St	O3	SM	SML	FC	SCL
Climate change	t CO_2 eq	5.5	5.5	11.1	10.8	24.9	10.1
Climate change/LULUC	t CO_2 eq	4.9	4.9	12.2	11.8	24.9	10.2
Cumulative energy demand	GJ	11.8	12.4	42.6	43.4	160.6	61.9
Eutrophication	kg PO_4^{3-} eq	19	19	42	45	53	53
Acidifcation	kg SO_2 eq	32	33	86	87	172	104

St: Standard suckler cow-calf herd with finishing heifers

O3: Suckler cow-calf herd with finishing heifers enriched in omega-3 FAs through pasture and wrapped grass silage

SM: Standard bull-fattening herd using a diet rich in starch based on maize silage

SML: Bull-fattening herd using a diet rich in starch (based on maize silage) supplemented with linseeds

FC: Bull-fattening herd using a fibre-based concentrate diet

SCL: Bull-fattening herd using a starch-based concentrate supplemented with linseeds

LULUC: Land use and land use change

Table S6: Eutrophication (EP), Acidification (AP) and Land occupation (LO) per kg of carcass mass of four animal types delivered from the four production systems according to four allocation methods

	Fattened bull				Finished heifer		Finished cull cow		Breeding bull	
	St-SM	**O3-SML**	**St-FC**	**O3-SCL**	**St**	**O3**	**St**	**O3**	**St**	**O3**
	EP (g PO_4^{3-} eq/kg carcass mass)									
Mass allocation	81	82	72	82	110	108	120	119	115	114
Protein allocation	91	92	82	92	119	118	100	99	56	55
Economic allocation	94	95	85	95	113	112	98	97	71	70
Economic allocation with subsidies	88	89	79	89	103	101	90	89	64	64
	AP (g SO_2 eq/kg carcass mass)									
Mass allocation	144	147	141	147	182	186	204	207	189	194
Protein allocation	160	163	157	163	198	202	171	174	92	94
Economic allocation	165	169	162	169	188	191	167	170	117	119
Economic allocation with subsidies	155	158	152	159	170	173	153	156	106	109
	LO (m^2a/kg carcass mass)									
Mass allocation	35.6	34.7	32.8	33.7	59.2	58.5	61.4	59.9	61.1	60.1
Protein allocation	40.6	39.6	37.8	38.6	64.2	63.4	50.7	49.5	29.7	29.2
Economic allocation	42.3	41.3	39.5	40.3	61.0	60.2	49.4	48.3	37.7	37.1
Economic allocation with subsidies	39.1	38.2	36.3	37.1	55.2	54.5	45.2	44.2	34.2	33.7

St: Standard suckler cow-calf herd with finishing heifers

O3: Suckler cow-calf herd with finishing heifers enriched in omega-3 FAs through pasture and wrapped silage

SM: Standard bull-fattening herd using a diet rich in starch based on maize silage

SML: Bull-fattening herd using a diet rich in starch (based on maize silage) supplemented with linseeds

FC: Bull-fattening herd using a fibre-based concentrate diet

SCL: Bull-fattening herd using a starch-based concentrate supplemented with linseed

Table S7: Impacts of beef meat product (per kg of carcass mass) delivered from the four beef-production systems and of activities for maintaining ecosystem services (per ha of grassland) from two suckler cow-calf herds with finishing heifers using economic allocation with agro-environmental subsidies

	Beef				Activities for maintaining ecosystem services	
	St-SM	O3-SML	St-FC	O3-SCL	St	O3
	per kg carcass mass				per ha of grassland	
Climate change (kg CO_2 eq)	25.6	25.6	25.8	24.8	557	563
Climate change/LULUC (kg CO_2 eq)	23.6	23.6	23.4	22.5	495	501
Cumulative energy demand (MJ)	60.2	63.6	68.8	66.3	1192	1261
Eutrophication (g PO_4^{3-}eq)	91	91	86	91	1984	1966
Acidification (g SO_2 eq)	157	160	155	160	3293	3367
Land occupation (m^2a)	44.0	43.2	42.6	42.7	1052	1039

St: Standard suckler cow-calf herd with finishing heifers

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FC: Bull-fattening herd using a fibre-based concentrate diet

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