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Keywords

Life-cycle Analysis; Beef production; Greenhouse gas emissions; Energy consumption; Land use

Abstract

To meet the increasing market demand for store male calves sold in summer, cow-calf beef cattle producers from the Charolais area, France, can opt for various strategies including changing the calving period. The objective of our study was to analyze and compare the impacts on greenhouse gas emissions (GHG), energy consumption and land use of two grassland-based cow-calf beef systems in relation to their contrasted grassland management and animal production strategies. Based on repeated measurements over 2 years, we carried out a Life-Cycle Analysis on two systems designed on an experimental farm. The Aut-system was based on autumn-calvings that required budgeting for a sufficient quantity and quality of grass fodder stocks harvested to cover the high feed demands of winter-lactating cows. The Spr-system was based on spring-calvings so that the peak needs of the herd and the breeding cows coincided with peak pasture grazing period. Management of male calves relied on a more intensive use of concentrate in the Aut-system. This study showed that at identical beef live weight produced, the Spr-system required 18% more on-farm utilized agricultural area, excreted 14% more nitrogen and released 12% more enteric methane, but used 22% less mineral nitrogen fertilizer, 34% less fuel, 89% less off-farm fodder purchases, 73% less concentrate purchases and 5% less bedding straw purchases. Livestock emissions per animal were close between the two systems and accounted for 75% of gross GHG emissions. As the Aut-system had a higher animal productivity, it was able to dilute this impact at identical live weight produced (4% higher gross GHG emissions in the Spr-system). This higher productivity also enabled the Aut-system to use less land (13% higher land use in the Spr-system) but relied on greater use of inputs (31% lower energy consumption in the Spr-system). As the Aut-system involved a lower surface area to produce beef, it reduced the potential of carbon storage by grassland to offset gross GHG emissions. This is the reason why the Spr-system led to 9% lower net GHG emissions. This mixed bag of results raises the question of the relative weight lent to each environmental impact and of the complementarities between strategies in grassland-based systems at region-wide scale.

1 Introduction

In the Charolais area, a pastureland region of specialized beef cattle farming in the French Massif Central, the downstream value chain wants to push its offer of store male calves in the off-season (June–July) so as to better gear livestock supply to market demand. To meet this raising commercial objective, cow-calf producers can pick from a variety of grassland management and animal production strategies including changing the calving period which was traditionally in spring. In a global context where livestock farming has been under fire as a driver of negative impacts on climate change, energy consumption and land use (Milne, 2005; Steinfeld et al., 2006), there is a need to understand the impacts of these new breeding strategies.

In the last decade, a large number of studies have been carried out to assess the environmental impacts of different farming systems (Bockstaller et al., 1997; Van der Werf and Petit, 2002; Halberg et al., 2005) including beef livestock systems (Casey and Holden, 2006; Beauchemin et al, 2011). These studies have implemented a number of methods including Life-Cycle Analysis (LCA) which is a holistic method to evaluate the use of resources and emission of pollutants during the entire life cycle of a product (Lee et al., 1995; De Vries and De Boer, 2010; Place and Mitloehner, 2012). These analyzes have aimed to compare the impacts of different systems according to types of production, scales and breeding practices. For example, they have investigated different steer finishing strategies (Pelletier et al., 2010), suckler vs suckler-to-finish systems (Eady et al., 2011), specialized vs mixed-livestock systems featuring different combinations of animals produced (male/female, age and finishing schemes) (Veysset et al., 2010), grassland vs non-grassland systems (Pelletier et al., 2010; Ridoutt et al., 2011). The LCAs performed have mainly been based on farm-modelling data rather than field data (Veysset et al., 2014).

The objective of our research was to analyze and compare the impacts on greenhouse gas emissions (GHG), energy consumption and land use of two grassland-based cow-calf beef systems in relation to their contrasted grassland management and animal production strategies. These two systems were studied on an experimental farm of the Charolais area over two years. They were designed to sell store male calves in June in line with the market demand but with distinct strategies coherent with their calving period: either spring or autumn. As collecting good-quality well-documented data is a key pillar of LCA-method reliability (Lee et al., 1995), we carried out a LCA based on repeated measurements.

2 Materials and Methods

LCA offers a transparent method for assessing the environmental impacts tied to the life cycle of a product. Such approach requires to define precisely the boundaries of the studied system and to quantify the emissions of pollutants and the use of resources along the production cycle of one functional unit, which is the main function of the production system expressed in quantitative terms (De Vries and De Boer, 2010; Veysset et al., 2014). For convenience, the different factors causing the emissions of pollutants and the use of resources will be grouped in the following text under the generic term of "sources of environmental impacts" (SEI).

2.1 Characteristics of autumn and spring calving systems

This experimental animal trial was performed in full compliance with all governing French ethics and welfare legislation. Two Charolais beef cow-calf systems were set up in 2010 on the Jalogny experimental farm (N 46°25' 6.251" E 4° 37' 49.511") and tracked over two production campaigns: 2011 and 2012. Each 12-month-long production campaign started in late March with a rotational grazing period (lasting about 8 months) followed by a period overwintering indoors in deep bedded freestalls until the following spring. The two systems were grassland-based systems that aimed to use a modest level of feed supplements to produce store male calves which could be sold in June, in line with the market demand. To achieve this goal, each system was managed under its own grassland management and animal production strategies. Animal production strategy embraced the choice of the calving period and the feeding strategy (**Fig.1**)

The autumn-calving system ('Aut') was based on calvings from August to October that required budgeting for a sufficient quantity and quality of fodder stocks harvested to cover the high feed demands of winter-lactating cows. The nutritionally-rich winter rations were based on a large share of early-mown pasture as silage (60% of winter rations) mixed with hay (40% of winter rations).

Male calves management was relatively intensive (1.2 kg DM of concentrate/calf per day) in an effort to get them to the target weight of 350 kg ready for sale directly post-weaning at 8–10 months.

The spring-calving system ('Spr') was based on calvings from late-February to April so that the peak needs of the herd and the breeding cows coincided with peak pasture production. Winter-season rations were hay-based (65% of winter rations) but also included grass baled silage (35% of winter rations). After weaning in November at 8–10 months of age, male calves were overwintered indoors then turned back out to pasture, after which they were sold at age 14–16 months at a target live weight of 450 kg. The more extensive management of male calves was less reliant on concentrate inputs than the Aut-system (0.5 kg DM of concentrate/calf per day). In both systems, winter rations of cows and heifers were complemented with small amounts of concentrate.

Cow-calf systems are the primary source of impact for beef production (Beauchemin et al., 2010; Nguyen et al., 2012) and a lot of cattle breeders of the Charolais area only produce store animals which are sold and finished in Italy. This is the reason why we did not include the finishing phase of animals in our trial. The two systems had a similar number of calvings (**Table 1**) at just over 50 a year (the light difference between the two systems was only due to practical constraints). To compare the production, intake and impacts of herds with different animal categories and distinct animal's numbers, we used the system of livestock unit (LU) presented in **Table 2**, inspired by Institut de l'Elevage (2000) and Vilain (2008). The two systems were designed to have a similar stocking rate around 1.15 LU/ha of grassland. Stocking rate is an indicator of the ability of grassland production to feed the herd (Delaby et al., 1998). In this study, we compared grassland management and animal production strategies at similar stocking rate in order to highlight the impact of external inputs used in beef production with a similar grassland production potential to feed the herd. As the Spr-system meant male calves spent more time on farm before going to market, the number of LU was higher in the Spr-system than in the Aut-system. The Spr-system was thus allotted a greater surface area to end up with the same stocking rate. The plot allotments chosen for each system were deemed to offer identical agronomic potential based on observations from previous years. Most utilized agricultural area was covered by grassland but each system included a minor cropping area to be self-sufficient on cereal grain (**Table 1**). All the harvested straw was used for bedding but most of bedding straw had to be purchased off-farm. Mean plot-to-barns distance was identical in both systems, at 5.6 km.

In both cases, replacement rate was 30%. Heifers not replacing cows and culled cows were sold. Reproduction practices were led in order to achieve one calving per cow per year. In the Spr-system, as the reproduction period (from May to July) took place outdoors, all cows were serviced by bulls (3.8 LU: three adults and one young bull). In the Aut-system, as the reproduction period took place indoors (from November to January), only half of the cows were serviced by bulls (2 LU: two adults), the other half were inseminated, reflecting local farmers' practices. In average, the age of cows at first calving was around 3 years. In both systems, open pasture and harvested fodder management practices were adjusted in response to the weather conditions registered in each campaign (790 and 1090 mm of rainfall in 2011 and 2012, respectively). However, these adaptations were made to fit with the wider initial strategy adopted.

2.2 Systems boundaries and functional unit

As our objective was to analyze and compare the environmental impacts of two farming systems in their whole, we considered systems boundaries from "cradle to farm-gate" (Casey and Holden, 2006; Monti et al. 2009), integrating all the processes upstream of farm production up to the moment the products leave the farm. Two types of impacts were considered: (i) direct impacts tied to on-farm production processes and activities; and (ii) indirect impacts tied to the manufacture (off-farm) and transport of all intermediate consumption, services and fixed assets needed as inputs to the production system. (Veysset et al. 2014). The main production function of the studied systems was beef. Each system sold different categories of store cattle (calves, heifers, culled cows) to fattening operations outside the farm. We therefore chose as functional unit the quantity of live weight produced (LWP) during one year (Pelletier et al., 2010; Veysset et al., 2014). It included the production of animals sold during the campaign (generating an income) and the production of growing animals not sold during the campaign (generating no income but creating economic value).

All animals were weighed at start (LWstart) and end (LWend) of the campaign. The LWP of each animal over the course of a campaign was calculated in kg of live weight (kglw) via equation **(1)**:

LWP=LWend-LWstart **(1)**

If the animal was sold mid-campaign, its weight at sale was taken as LWend. If the animal died mid-campaign, LWP was zero as the beef produced was not marketable. For a calf born during the campaign, LWstart=0, which equated to allotting their intrauterine growth to this campaign. For cows in gestation, weight of uterine content (foetus plus amniotic sac) was calculated at weighing according to Bereskin and Touchberry (1967) and subtracted from measured bodyweight. Weight variations in adult cattle not sold during the year were considered as physiological adjustment without market value. The beef production of cows not sold during the year was therefore considered zero after first calving. The LWP of each system over the course of a campaign equated to the sum of the LWP of every in-system animal in-campaign.

2.3 Diet and feeding

2.3.1 Measurements of feeds distributed indoors

The amounts of fodder and concentrate distributed during the winter period were measured daily. All feeds offered were analyzed in-lab to determine their physical-chemical characteristics (dry matter DM, organic matter OM, crude protein CP) and estimate digestibility (OMd) and feed values according to the INRA feed system (Baumont et al., 2010) as net energy (NEL) and metabolizable protein (MP), and their fill factors (in CFU). Theoretical feed-energy requirements were also calculated in the same feed system (Agabriel and D'hour, 2010; Agabriel and Meschy, 2010) to check that energy supplied to the animals was coherent with energy requirements.

2.3.2 Estimation of animal intake at grazing

Intake at grazing was calculated using the INRA system of cattle fill units (CFU) as detailed in Delagarde et al. (2001). Daily amount of grass intake in kg dry matter (AI_gr) was estimated per animal via equation **(2)** by factoring in intake capacity (IC), fill factors of any feeds distributed as supplementation to pasture grass (Fill_feed) and fill factor of the pasture grass grazed (Fill_grass) weighted by an accessibility–grazability coefficient (Acc_grass) linked to available biomass.

$$AI\_gr=((IC-Fill\_feed)/Fill\_grass)*Acc\_grass \quad (2)$$

For this estimate, grazing period was split into 3 sub-periods of around 2½ months each. Body weight and body condition score were systematically measured at the start and end of each sub-period in order to calculate the IC and energy and protein requirements of each animal (Agabriel and Meschy, 2010). Where concentrate and fodder were distributed as supplementation to grazed pasture grass, we ran exactly the same intake and physical–chemical characterization measurements as for indoors rations, including fill (Fill_feed) expressed in CFU. The Acc_grass coefficient, expressed as a percentage, was calculated for each sub-period by factoring in available grass biomass (Bio_gr_avail) based on equation **(3)** from Jouven et al. (2008).

$$Acc\_grass= 1-\exp(-0.0012*Bio\_gr\_avail) \quad (3)$$

Bio_gr_avail, expressed in kg DM/ha, was estimated by coupling grass height measurements using a plate pasture meter to grass cover density measurements. Each grass height estimate corresponded to a mean of 42 measures per plot taken randomly at 25-pace intervals zigzagging through the plot. This number of measurements follows the system proposed by Mathieu and Fiorelli (1985) and Nielsen et al. (2004). Grass cover density measurements were performed in the 2012 campaign only, based on grass samples mown at 5 cm gauge aboveground on 6 separate 50×50-cm quadrats evenly distributed across each plot, as per Defrance et al. (2004). Grass height, cover density measurements and physical–chemical analyses were performed each time the animals were rotated to a fresh grazing plot, which thus equates to a mean of 18 estimates per sub-period per system.

Grass height measurements were averaged for each sub-period in each system and each campaign. The grass cover density measurements were averaged for each sub-period of the 2012 campaign and allotted to the corresponding sub-periods of the 2011 campaign. For each grazing sub-period, we calculated the mean available grass biomass (Bio_gr_avail) by multiplying mean grass height by mean grass cover density.

In order to estimate Fill_grass, we purpose-developed a specific approach to take into account the variability of grazing conditions depending on weather events. We worked to the premise that variations in heifers' growth reflected increased or decreased intake due to weather conditions of each grazing sub-period. Amount of grass intake by heifers, AI_gr, was first estimated for each sub-period based on their weight gain and the energy value of the grass offered (Agabriel and Meschy, 2010). Applying the resulting value in equation (2) made possible to estimate Fill_grass. The Fill_grass values thus obtained were 1.1 CFU/kgDM and 1.2 CFU/kgDM for the first sub-period of 2011 and 2012, respectively, and 1.0 CFU/kgDM and 1.1 CFU/kgDM for second/third sub-periods of 2011 and 2012, respectively. These calculated values were often higher than the fill measured by chemical analysis as they integrated weather conditions with more or less negative impact on grazing. Based on the premise that these conditions were identical across all the animal lots, this grass fill value was allotted to all cattle lots and animal categories in the AI_gr calculation. We validated that the estimates of intake at grazing were coherent with the performances of non-heifer lots by ensuring that the dietary energy and protein inputs covered the theoretical energy and protein requirements calculated (Agabriel and D'hour, 2010).

2.4 Quantifying environmental impacts

Three environmental impact categories related to beef production (Steinfeld et al., 2006) were studied: global warming due to the greenhouse gas (GHG) emissions generated, energy consumption and land use. For GHG, SEI were listed (Table 3) following the GES'TIM approach (Gac et al. (2010a). GES'TIM is a methodology for assessing CHG emissions in French livestock systems whose precision is classed at level 2 (Tier 2) according to the IPCC rankings (IPCC, 2007) which means that it uses values adapted to national-specific configurations (Veysset et al., 2014). For energy consumption and land use, SEI were inventoried following the yet unpublished Environmental Multi-criteria Analysis developed by Institut de l'Elevage (the French National Institute for Livestock) inspired by Ecoinvent (2009) and ADEME (2013). We aimed to realize the LCA based on repeated field measurements in order to guarantee its reliability (Lee et al., 1995).

For practical constraints, we focused the measurement process on eight SEI singled out for their major role in the studied impacts (Pervanchon et al., 2002; Galan et al., 2007; Beauchemin et al., 2010; Pelletier et al., 2010, Veysset et al., 2014). The other SEI were estimated as described in Table 3. As the two systems had different numbers of animals from different categories, SEI were expressed on a per-LU basis to link the environmental impacts to livestock management. SEI per LU represent the environmental impacts of breeding one full size animal over one year (Table 2). SEI were also expressed on a per-100 kg LWP basis to relate them to beef production.

Nitrogen excreted by the animals (Nex) was calculated using the equation **(4)** from nitrogen ingested (Ning) by the animals and nitrogen fixed (Nfix) in the body (CORPEN, 2001):

$$\mathbf{Nex=Ning-Nfix} \qquad \mathbf{(4)}$$

Ning was obtained from measured feed intakes and estimated on-pasture grass intakes multiplied by their respective nitrogen content. Nfix was calculated for each animal multiplying total campaign LWP × nitrogen content in the live weight. Nitrogen content in the live weight (g N/kg LWPLWP) is age-dependent and thus modulated as per Garcia et al. (2010): 35.2 for calves aged under 12 months, 32 at 12–24 months, 28.8 at 24–36 months, and 25.6 at 36-plus months. This particular calculation took into account the live weight produced by animals that died and weight variations in adult cattle not sold during the campaign, as they accounted for Nfix even if there was no way of marketing this LWP. Enteric methane (Met) emissions from the animals were calculated from the intake levels and chemical composition (DM, OM, OMd) of the rations, using equation 9 from Sauvant et al. (2011). Mineral nitrogen applied (Nmin) was measured in each system. We assumed that this nitrogen was all taken up in one year, without any change in soil nitrogen status before and after the experiment. Fuel consumption was measured by equipping each of the two main tractors used (110 hp and 95 hp models) with a fuel consumption reader. When other motor-driven farm machinery was used, fuel consumption was measured by the level difference in the tank after the operation. Fodder (F_purch) and bedding straw (S_purch) purchased off-farm were weighed along with the veal feed supplement and nitrogen supplement concentrate purchased (C_purch). In theory, the two systems were designed to be forage self-sufficient, but in practice, a few fodder purchases had to be made especially in spring 2011 that was particularly dry. The On-farm utilized agricultural area (UAA) was the total farmland area allocated to the system, covering the grassland area plus cereal crop acreage used to feed each system herd (**Table 1**).

Direct nitrous oxide (N_20) and methane (CH_4) emissions associated to SEI were calculated as per Gac et al. (2010a). Other direct and indirect CHG emissions and energy consumption related to SEI were aggregated into kg CO_2e and MJ, respectively, based on the coefficients endorsed by the French National Agency for Environment and Energy (ADEME, 2013). GHG emissions from all SEI were converted into carbon dioxide equivalent (kg CO_2e) using IPCC (2007) conversion factors (CO_2=1, CH_4=25, N_20=298). Only gross emissions of GHG were quantified (without considering the offset potential of carbon storage in grasslands and hedges which will be addressed in the discussion part). To calculate the land use, UAA was added to the indirect impact of other SEI converted into m² based on the coefficients endorsed by Ecoinvent (2009). These coefficients provide an estimation of the land used off-farm to manufacture and transport different inputs such as feed, fuel, mineral nitrogen and electricity.

2.5 Estimation of carbon storage capacity

The GHG emissions detailed in the previous paragraph are gross emissions, i.e. that do not account for the role of grasslands and hedgerows as a carbon sink. The offsetting of GHG emissions allowed by carbon storage is nevertheless an important factor in grassland-based systems analysis (Gac et al., 2010b). The carbon storage capacity of grassland is highly variable, as there is an array of factors to account for type of grassland, grazing pressure, grassland history and climate (Soussana et al., 2010). It was estimated for both studied systems based on elements presented in **Table 4** and net GHG emissions were calculated using equation (**5**):

$$\textbf{Net GHG=Gross GHG- carbon storage capacity} \quad \textbf{(5)}$$

2.6 Statistical analysis and comparisons between systems

All data were analyzed per system and per production campaign. Results on a per-LU, per-100 kg LWP or per-hectare basis were aggregated over the two campaign-years using weighted means. Fuel and nitrogen fertilizer consumption per hectare were analyzed using the same SAS-bundled GLM procedure testing system, year and plot-use practices as fixed effects (SAS version 9). All assumptions were checked and validated for normality and homoscedasticity of residuals.

3 Results

3.1 Animal intake and live weight production

Spr-system animals had a higher grass intake than Aut-system animals (2.38 t DM/LU vs 2.68 t DM/LU; (Spr-Aut)/Aut: +12%) which in turn consumed more stored fodder (Aut: 1.98 t DM/LU vs Spr: 1.55 t DM/LU; (Spr-Aut)/Aut -22%) and more concentrate (Aut: 0.29 t DM/LU vs Spr: 0.19 t DM/LU; (Spr-Aut)/Aut -37%) than Spr-system animals (**Table 5**). These figures are fully consistent with the feed strategies employed in each system.

Over the two years studied, the Aut-system produced 48,539 kg LWP and the Spr-system produced 50,902 kg LWP. Male calves were sold at an average weight of 359(45) kg LWP in the Aut-System and 464(54) kg LWP in the Spr-system in line with the target of each system. Animal productivity, which is the amount of LWP per LU, was higher in the Aut-system (Aut: 325 kg LWP vs Spr: 283; (Spr-Aut)/Aut: -13%). In both systems, most of LWP was produced by growing animals (**Table 6**), either heifers (Aut: 55% of global LWP vs Spr: 51%) or male calves (Aut: 43% of global LWP vs Spr: 48%). The higher productivity of the Aut-system was explained above all by the higher productivity of male calves (Aut: 1851 kg LWP/LU vs Spr: 998kg LWP/LU; (Spr-Aut)/Aut: -46%). Heifers performance was really close in both systems compared to other animal categories (Aut: 367 kg LWP/LU vs Spr: 368 kg LWP/LU; (Spr-Aut)/Aut: -0.3%). Even, if LWP of adult cows was really low in both systems, cows of Aut-system had a higher productivity (Aut: 5 kg LWP/LU vs Spr: -8 kg LWP/LU).

3.2 Sources of environmental impacts quantified through measurements

SEI quantified through measurements are all presented calculated on an LU and LWP basis in **Table 7**.

3.2.1 Livestock emissions

On a per-LU basis, livestock GHG emissions were close between systems compared to the variability highlighted in literature (Gac et al., 2010a; Sauvant et al. 2011) , whether due to Nex (Aut: 103.5 kg N vs Spr: 102.5; (Spr-Aut)/Aut: -1%), or enteric methane Met (Aut: 111 kg CH_4 vs Spr: 108; (Spr-Aut)/Aut: -2%). However, on a per-100 kg LWP basis, the Spr-system was a bigger Nex emitter (Aut: 32 kg N vs Spr: 36; (Spr-Aut)/Aut: +14%) and Met emitter (Aut: 34 kg CH_4 vs Spr: 38; (Spr-Aut)/Aut; +12%).

3.2.2 Mineral fertilizer and fuel

To ensure greater stocks of better-feed-value fodder, the share of silaging was higher in the Aut-system (28% of plot allotment) than in the Spr-system (11% of plot land), as was percentage share of twice-mown plots (16% of plot allotment in the Aut-system vs 4% in the Spr-system), as shown in **Fig.2**. These differences in management practices led to higher Nmin and fuel consumption per ha in the Aut-system (**Table 8**) because mean fertilizer input and fuel consumption increased with increased silaging and number of cuts a year per plot (**Fig. 3** and **Fig.4**). On a per-LU basis, Nmin was higher in the Aut-system (Aut: 35 kg N vs Spr: 24; (Spr-Aut)/Aut: -32%) but the gap got narrower when Nmin was expressed on a per-100 kg LWP basis due to the better productivity of Aut-system animals (Aut: 11 kg N vs Spr: 8; (Spr-Aut)/Aut: -22%).

Fuel consumption in both systems was shared between the fuel used for the various cropping operations in the plot allotment (**Table 8**) scheme and the fuel demand needed for overwintering work required while the animals are housed indoors, i.e. feed dispensing, bedding and mucking out the cowsheds. In terms of winter-season operations, the Aut-system used more fuel per LU (Aut: 36 L vs Spr: 14; (Spr-Aut)/Aut: -61%). This difference was largely explained by the fact that the Aut-system used a mixer-wagon to prepare and distribute the grass silage-based feed rations whereas the Spr-system used a bale-feeder that needed less motive power—and thus less fuel. Consequently, the Aut-strategy forage system ended up using more fuel to build up fodder stocks and more fuel to distribute them, which ultimately translated into higher total fuel consumption per LU (Aut: 86 L vs Spr: 49; (Spr-Aut)/Aut: -43%) and on a per-100 kg LWP basis (Aut: 27 L vs Spr: 17; (Spr-Aut)/Aut: -34%).

3.2.3 Feed and bedding straw purchased off-farm

Aut-system herd management required higher off-farm feed purchases per LU than Spr-system herd managements: both on F_purch (Aut: 253 kg DM vs Spr: 24 kg; (Spr-Aut)/Aut; -90%) and C_purch (Aut: 164 kg DM vs Spr: 39 kg DM; (Spr-Aut)/Aut: -76%) These gaps remained just as high when the amounts were expressed to per-100 kg LWP, both on F_purch (Aut: 78 kg DM; Spr: 9; (Spr-Aut)/Aut; -89%) and C_purch (Aut: 50 kg DM; Spr: 14; (Spr-Aut)/Aut; -73%). These results were coherent with the Aut-system strategy that revolved around faster calves' growth, which hinged on greater feed and nitrogen supplement concentrate purchases. The amount of purchased bedding straw was lower per LU in the Spr-System (Aut: 1211 kg DM vs Spr: 1000 kg DM; (Spr-Aut)/Aut: -17%) because winter rations of the Spr-system had a higher dry matter content (Aut: 0.46 vs Spr: 0.75; (Spr-Aut)/Aut: +62%) related to dryer feces requiring less bedding straw. This difference was lowered when S_purch was calculated per 100 kg LWP (Aut: 373 kg DM vs Spr: 354 kg DM; (Spr-Aut)/Aut: -5%).

3.2.4 Utilized agricultural area

On a per-LU basis, UAA was close between the two systems compared to other SEI (Aut: 8926 m^2 vs Spr: 9111; (Spr-Aut)/Aut: +2%). However, the better productivity of the Aut-system made possible to use less farmland to produce the same LWP as shows the UAA calculated on a per-100kg LWP basis (Aut: 2727 m^2 vs Spr: 3221; (Spr-Aut)/Aut: +18%).

3.3 **Impact of beef production on GHG, energy consumption and land use**

Impact of beef production on gross GHG emissions, energy use and land use for each system are presented in **Fig. 5**. Carbon storage capacity and net GHG emissions are presented in **Fig. 6**.

3.3.1 GHG emissions

The impact of beef production on gross CHG emissions, expressed per 100 kg LWP, was lower under the Aut-system than the Spr-system (Aut: 1,540 kg CO_2e vs Spr: 1,598; (Spr-Aut)/Aut: +4%). Animal-released gas emissions (Nex and Met) accounted for the bulk of this global warming impact: 72% of Aut-system impact and 79% of Spr-system impact.

As the Spr-system used a greater grassland area than the Aut-system to produce 100 kg LWP of beef, its carbon storage potential was higher per 100 kg LWP (Aut: 748 kg CO_2e vs Spr: 874; (Spr-Aut)/Aut: +17%). The net GHG emissions expressed per 100 kg LWP were therefore lower in the Spr-system (Aut: 792 kg CO_2e vs Spr: 724; (Spr-Aut)/Aut: -9%).

3.3.2 Energy consumption

Beef production required greater energy input under the Aut-system strategy than the Spr-system strategy, as shown when consumption is expressed per 100 kg LWP (Aut: 2,276 MJ vs Spr: 1,567; (Spr-Aut)/Aut: -31%). Fuel consumption and use of mineral nitrogen accounted for the bulk of this energy use impact: 76% of Aut-system impact and 77% of Spr-system impact.

3.3.3 Land use

The Aut-system required less land than the Spr-system to produce the same amount of beef, as shown when land use is expressed per 100 kg LWP (Aut: 2,951 m^2 vs Spr: 3,325; (Spr-Aut)/Aut: +13%). Off-farm inputs (Fuel, Nmin, F_purch, S_purch and C_purch) had relatively low indirect impact on land use, since UAA accounted for 94% of Aut-system land use and 97% of Spr-system land use.

4 Discussion

4.1 Variation in results from campaign to campaign

Animal production and grassland management practices were adjusted in each campaign-year mainly in response to weather conditions. For example, 2012 was a wet year and enabled more plots to be harvested for fodder than in 2011 where the dry spring forced the number of mowings to be revised downward, leaving the available grass cover to pasture. This higher number of mowings in 2012 led to greater fuel consumption. Conversely, in 2011, to contend with the shortage of fodder crops to make it through winter, catch crop cover was sown after the cereal crops and harvested before the winter, which also led to excess fuel consumption. The 2011 catch crops were counterbalanced by a higher number of mowings in 2012. Moreover, the amount of concentrate distributed per LU and the share of concentrate purchased off-farm varied over the two campaigns (**Table 5** and **Table 7**) which lead to affect different surfaces area of cereal crops to each system and campaign (legend of **Table 1**). These variations were related to adaptation to weather conditions or to tactical change in feeding strategy. As 2012 allowed a bigger forage stock, less concentrate was distributed in the Spr-system. In 2011 the winter ration of Aut-system calves was based on commercial concentrate in order to secure their growth but in 2012 the staff of the experimental farm judged that cereals produced on-farm could replace part of it and ensure the same performance (leading to more direct land use but less indirect land use in 2012). These tactical adjustments had no effect on the value ranges or respective rankings of the systems in each SEI. Ultimately, environmental impacts in both systems over both years ended up at practically the same bottom-line values, even if the balance between SEI was put together differently.

While the SEI values remained very similar from year to year, live weight production showed year-on-year variability. Both systems were effectively built around an essentially grass-based diet with relatively little added concentrate, which made them potentially sensitive to climate-driven variations in grass input. Paradoxically, the climate enabled better-quality grazing and fodder conditions in 2011 and the live weight production per LU aggregated from both systems was 17% higher than in 2012, despite a lower net rainfall. Measurements on the environmental SEI in the two years turned out practically identical, but the greater per-LU productivity in 2011 enabled more environmentally efficient farm production. Nevertheless, to deeper analyze the climate factor-sensitivity of the results, it would be necessary to observe and collect data on the systems over more than just two years so as to extend and expand the range of extreme weather settings registered.

4.2 Dealing with LCA uncertainties

Huijbregts et al. (2003) identified three sources of uncertainty in LCA approaches: parameter uncertainty, scenario uncertainty and model uncertainty. Model uncertainty relies here on the references used to quantify the environmental impacts tied to the different measured SEI and to aggregate them in a common unit for each environmental impact category (Ferrand et al., 2012). These references came from peer-reviewed scientific literature and approved LCA methodologies. There is no element in our experimental trial to discuss them.

Parameter uncertainty reflects the limitation of knowledge about the value of SEI. In our study, we tried to address this issue with the collect of precise data through repeated measurements (Lee et al., 1995; Huijbregts, 1998). Some SEI (electricity, methane emissions from feces and manure storage, N20 emissions from N leaching, run-off, volatilization, ploughing up grasslands in the rotation and mineralization from crop residues) were not quantified through measurements but they accounted in average for 9% of the impacts on gross GHG emissions and energy consumption and 0% of land use. In particular, non-measured methane emissions from feces and manure storage represented 7% of the gross GHG emissions (more than measured N_min, Fuel, F_purch, C_purch, S_purch) and are therefore a major impact driver of climate change in beef production systems as shown by Veysset et al. (2014). On-farm measurements of these emissions would improve the reliability of our study.

Scenario uncertainty is related to the unavoidable normative choices made about functional unit and systems boundaries. As in other studies (Pelletier et al., 2010; Veysset et al., 2014), the functional unit chosen in this study was kg of live weight produced because the two systems sold store cattle for further fattening operations. However, the final product expected by consumers is meat but dressing percentage (conversion factor from live weight to meat), protein and fat content of meat are (among others) age and sex dependent (Garcia et al., 2010). As the two systems sold female and male animals from different ages, further investigation may be required for quantifying the impacts related to other functional units: kg of meat, edible protein or fat as suggested by De Vries and De Boer (2010). Moreover, the systems boundaries did not encompass the finishing of the animals produced by each system. However, as male calves were sold lighter in the Aut-system than in the Spr-system, the subsequent finishing phase would be longer.

4.3 Furthering the LCA considering the finishing phase

Based on previous unpublished studies of calves finishing led on the same experimental farm, we estimated that male calves from the Aut-system would require 242 days of finishing and Spr-system calves 164 days to reach a final target live weight of 730 kglw in the Aut-system and 750 kglw in the Spr-system (in line with local practices and market demand). In both cases, the calves would be fed grain maize, rapeseed meal and corn silage after a transition period of hay, grass silage, wheat and rapeseed meal. Using the same LCA methodology as in our trial, the environmental impacts of these contrasted finishing phases were quantified and aggregated to the results of our study (**Table 9**).

In both systems, the finishing phase would have lower environmental impacts per 100 kg LWP than the cow-calf production phase except for net GHG because the finishing phase would happen in indoors feedlots with no carbon storage capacity. Integrating the finishing phase of male calves into the boundary of the LCA would not change the relative position of both systems for the considered environmental impacts. Nevertheless, this integration would benefit more to the Aut-system which would produce more LWP in the finishing phase because the calves would start at a lower weight.

These estimations of the finishing phase did not include culled cows, heifers and breeding bulls. These animals would have similar finishing in both systems. As they were sold order than male calves, their finishing would require more fodder and concentrate (Garcia et al., 2010), more fuel for feed distribution and generate more GHG emissions (Gac et al., 2010a) per 100 kg LWP. Moreover, this finishing phase would lead to less impacts than the cow-calf phase which is the primary source of impact for beef production (Beauchemin et al., 2010). We can therefore hypothesize that including the finishing phase of culled cows, heifers and breeding bulls would lead ton intermediate impacts ranging between the cow-calf phase and the cow-calf+finishing phase and not change the relative position of each system related to the studied impacts.

4.4 Comparison of our results to previous literature

The objective of our study was to analyze and compare the relative impacts of two contrasted grassland-based cow-calf beef systems rather than to provide absolute values of their impacts. However, the GHG emissions of the two studied systems, including or not the finishing phase, were within the range of the previous study of Veysset et al. (2014) in the Charolais area based on data from 59 farms (including farms with finishing and without finishing): from 950 to 2113 kg eq CO2/100 kg LWP for gross GHG and from 727 to 1172 kg eq CO2/100 kg LWP for net GHG. The energy consumption of the Aut-system was also within the range of this study: from 1800 to 4900 MJ/ 100 kg LWP, whereas the Spr-sytem one was lower. This may be explained by the fact that the Spr-system designed on the experimental farm relied on a really extensive animal production strategy (in terms of concentrate per LU and Nmin per ha) which was not representative of local breeders' strategies who traditionally tend to have more intensive practices. The impacts on land use of the two studied systems were close to results of a LCA carried out by Nguyen et al. (2012) through modelling of different beef production systems in the Charolais area: from 3210 to 3310 m2/100 kg LWP for the cow-calf production phase (including the finishing of heifers) and from 360 to 780 m2/100 kg LWP for the finishing phase of male calves. The estimated gross GHG emissions of the cow-calf+finishing production phase were in the same order of magnitude as results obtained in other countries for beef production systems : 1320 kg eq CO2/100 kg LWP in the USA (Johnson et al., 2003) and 1172 kg eq CO2/100 kg LWP in Canada (Beauchemin et al. 2010).

4.5 Relations between management strategies and sustainability of the cow-calf systems

Several papers have shown that ration composition, chiefly proportion of concentrate in the diet system, had an impact on mean per-animal enteric methane emissions (Vermorel, 1995; Sauvant et al., 2011). The Aut-system and Spr-system did present differences in their winter-season ration compositions, but the vast majority of net dry matter intake by the animals came through grazing. While concentrate fraction was bigger in the Aut-system, it was on a modest level in both systems as they produced store animals that were not finished on-farm. The between-system differences in ration composition led to close levels of livestock emissions per LU (Met and Nex) which thus emerged as a relatively fixed environmental cost per LU and accounted for 75% of gross GHG emissions. Accordingly, the Aut-system strategy, which aimed to produce more beef per LU, can be regarded as a way to reduce the gross GHG emissions of beef farming, as suggested by Beukes et al. (2010). However, this increase in per-animal productivity hinged on greater inputs per LU (Nmin, fuel, F_purch, C_purch), which translated into a higher energy consumption per 100 kg LWP. In the Aut-system, this higher animal productivity also made it possible to use less land to 100 kg LWP. On the other side of the equation, the greater grassland area used in the Spr-system enabled a greater potential of carbon storage related to lower net GHG emissions.

Further investigating the economic performances and social impacts of these systems would help gauge their wider sustainability (Van Cauwenbergh et al., 2007). As the Spr-system had a higher energetic efficiency (using less inputs per 100 kg LWP), it may be related to higher economic gross margins (Veysset et al., 2014). On a social level, spring-calvings happen at a quiet period of the year in terms of workload dedicated to other farming tasks whereas autum-calvings happen in a busy period and may generate more stress. However, as the calving-period implicates for farmers to keep a close eye on the herd even through the night, some farmers may prefer autum-calvings when the nights are warmer in the Charolais area.

Conclusion

This study showed that two grassland-based cow-calf beef systems in the Charolais area, France, had contrasted environmental impacts connected to the contrasted grassland management and animal production strategies they employed. Compared to the Aut-system and at identical beef live weight produced, the Spr-system required 18% more on-farm utilized agricultural area, excreted 14% more nitrogen and released 12% more enteric methane, but used 22% less mineral nitrogen fertilizer, 34% less fuel, 89% less off-farm fodder purchases, 73% less concentrate purchases and 5% less bedding straw purchases. Livestock emissions per LU were close between the two systems and accounted for 75% of gross GHG emissions. As the Aut-system had a higher animal productivity, it was able to dilute this impact at identical live weight produced (4% higher gross GHG emissions in the Spr-system). This higher productivity also enabled the Aut-system to use less land (13% higher land use in the Spr-system) but relied on greater use of inputs (31% lower energy consumption in the Spr-system). As the Aut-system involved a lower surface area to produce beef, it reduced the potential of carbon storage by grassland to offset gross GHG emissions. This is the reason why the Spr-system led to 9% lower net GHG emissions.

As the two studied systems sold store male calves at different weight and age, we carried out an estimation of the impacts of their finishing. Including this finishing phase did not change the relative position of each system related to the studied impacts as the cow-calf production phase was the major source of impacts. This mixed bag of results raises the question of the relative weight lent to each environmental impact and of the complementarities between strategies in grassland-based systems at region-wide scale.

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Table 1: Characteristics of the two systems (means over the two production campaigns)

System	Aut	Spr
Utilized Agriculture Area (UAA) (ha)	66.6	82.0
including grassland (ha)	64.4	79.2
including cereal crops* (ha)	2.1	2.8
Number of calvings	51	54
Livestock Units of the herd	75	90
Global stocking rate (LU/ ha of grassland)	1.16	1.14

** The surface area of cereals crops given for each system is a mean between 2011 and 2012. The surface area dedicated to cereal crops was different in 2011 and 2012 for practical constraints (due to the size of plots included in the rotation). The production of cereals on these plots was always bigger than the herd requirements. As the excess cereals were sold off-farm and were not used for beef production, we affected to each system only the surface area necessary to cover its yearly cereal requirements (Aut-system: 1.5 ha in 2011 and 2.9 ha in 2012; Spr-system: 3.6 ha in 2011 and 2.1 in 2012). The causes and consequences of these variations from campaign to campaign were addressed in the discussion part.*

Table 2: Livestock Unit (LU) coefficients for the different animal categories, inspired by Institut de l'Elevage (2000) and Vilain (2002

Animal category	Livestock Unit coefficient
Bull	1
Cow	0.85
Heifer or bull 2-3 years	0.8
Young male 1-2 years	0.65
Heifer 1-2 years	0.6
Male calf 0-12 months	0.37
Female calf 0-12 months	0.35
Calf under 3 months	0

*The LU coefficients increase with the theoretical dry matter intake of animals. They correspond to a full year of presence in the corresponding category. The LU affected to each animal was a linear combination of these coefficients taking into account its presence time in the system (sometimes less than one full campaign when sold or dead) and potential category changes along the year. For example, to a male calf sold at 9 months was affected a LU of 0*3/12+0.37*6/12=0.175.*

Table 3: Sources of environmental impacts considered in the LCA and quantification methods

Sources of environmental impacts (SEI)	Direct and indirect environmental impacts			Quantification method
	GHG	Energy consumption	Land use	
Nitrogen excreted (Nex)	X			Based on measurements as described in the body of the text
Enteric methane (Met)	X			
Mineral nitrogen applied (Nmin)	X	X	X	
Fuel consumption (Fuel)	X	X	X	
Fodder purchased off-farm (F_purch)	X	X	X	
Concentrate purchased off-farm (C_purch)	X	X	X	
Bedding straw purchased off-farm (S_purch)	X	X	X	
On-farm Utilized Agriculture Area (UAA)			X	
Electricity	X	X	X	Expert estimation from electricity bills of the experimental farm
Methane emissions from feces	X			Estimations from GES'TIM approach (Gac et al. 2010a)
Methane emissions from manure storage	X			
N_20 emissions from N leaching, run-off, volatilization, ploughing up grasslands in the rotation and mineralization from crop residues	X			

Table 4: Elements considered for estimating carbon storage in each sytem

System	Landscape elements involved in carbon storage-release balance Aut	 Spr	References used***
Grassland	64.4 ha	79.2 ha	570 kg C/ha per year (Dollé et al. 2013 based on Schulze et al., 2009 and Soussana et al., 2010)
Hedgerows*	11,853 lm	14,604 lm	125 kg C/100 lm of hedgerows per year (Arrouays et al., 2002)
Cereal crops**	2.1 ha	2.8 ha	-950 kg C/ha per year (Arrouays et al., 2002)
Total			

*On the experimental farm, the average presence of hedgerows is 178 linear meter (lm) per hectare

** Cereal crops in rotation with grassland release carbon emissions because they require ploughing up grassland

***kg of C were converted into kg CO_2e multiplying by 44/12 (molar mass of CO_2 / molar mass of C)

Table 5: Animal intake for each system and production campaign

System		Aut		Spr	
Campaign		2011	2012	2011	2012
Animal intake (t DM/LU)	Grazed grass	2.18	2.60	2.75	2.61
	Stored fodder	1.98	1.98	1.52	1.58
	Concentrate	0.290	0.300	0.200	0.167

Table 6: Quantity of live weight produced (LWP) by the different animal categories (kg)

System	Aut								Spr							
Campaign	2011				2012				2011				2012			
Animal category	LWP	% of global LWP	LU	LWP/LU	LWP	% of global LWP	LU	LWP/LU	LWP	% of global LWP	LU	LWP/LU	LWP	% of global LWP	LU	LWP/LU
Cows	165	1%	32	5	131	1%	30	4	-106	0%	39	-3	-492	-2%	39	-13
Heifers*	14062	53%	37	381	12497	57%	35	353	15303	55%	36	425	10476	45%	34	308
Male calves**	11865	45%	6	1870	9051	41%	5	1827	11903	43%	11	1055	12362	54%	13	948
Breeding bulls	382	1%	2	191	384	2%	2	192	725	3%	4	191	730	3%	4	192
Total	**26475**	100%	**77**	344	**22063**	100%	**72**	305	**27826**	100%	**90**	308	**23076**	100%	**90**	257

** Includes all female animals from birth to first calving. LWP of replacement heifers which became cows along the campaign was affected to the heifers' category because they were still growing.*
*** Includes two generations of animals: the calves sold during the campaign and the calves born during the campaign which were sold in the next campaign.*

Table 7: SEI quantified through repeated measurements for each system and production campaign

	/LU						/100 kg LWP					
System	Aut		Spr		(Spr-Aut)/Aut		Aut		Spr		(Spr-Aut)/Aut	
Campaign	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
Nex (kg N)	102	105	106	99	**5%**	**-6%**	30	35	35	38	**+17%**	**+11%**
Met (kg CH_4)	106	115	111	105	**5%**	**-9%**	31	38	36	41	**+17%**	**+7%**
Nmin (kg N)	37	33	23	24	**-37%**	**-27%**	11	11	8	9	**-30%**	**-13%**
Fuel (L)	77	96	50	49	**-35%**	**-49%**	22	31	16	19	**-28%**	**-40%**
F_purch (kg DM)	352	146	22	26	**-94%**	**-82%**	103	48	7	10	**-93%**	**-78%**
C_purch (kg DM)	220	104	27	50	**-88%**	**-52%**	64	34	9	20	**-86%**	**-43%**
S_purch (kg DM)	1233	1187	1046	953	**-15%**	**-20%**	359	390	340	371	**-5%**	**-5%**
UAA (m^2)	8356	9387	9063	9119	**7%**	**-3%**	2432	3082	2947	3553	**+26%**	**+15%**

Table 8: Mean fuel consumption and mineral fertilizer input per hectare

System	Aut		Spr	
Campaign	**2011**	**2012**	**2011**	**2012**
Number of plots*	25	27	31	35
Fuel for cropping operations(L/ha)	55 (60)	52(40)	37 (45)	34 (29)
Nmin (kgN/ha)	39 (45)	30 (33)	20 (33)	24 (26)

**The variation in the number of plots of each system is due to the adaptation of grazing practices to climatic conditions. The 2012 campaign had higher rainfalls than 2011 and some plots were subdivided to better manage the grass growth.*

Table 9: Live weight production, carbon storage and environmental impacts for the different production phases of the two systems

	Production phase	**Aut**	**Spr**	**(Spr-Aut)/Aut**
LWP (kg)	cow-calf	48539	50902	**+5%**
	finishing	17808	13728	**-27%**
	cow-calf+finishing	66347	64630	**-4%**
Gross GHG (kg eq CO2/100 kg LWP)	cow-calf	1540	1598	**+4%**
	finishing	893	905	**+1%**
	cow-calf+finishing	1366	1451	**+6%**
Carbon storage (kg eq CO2/100 kg LWP)	cow-calf	748	874	**+17%**
	finishing	0	0	**0%**
	cow-calf+finishing	547	689	**+26%**
Net GHG (kg eq CO2/100 kg LWP)	cow-calf	792	724	**-9%**
	finishing	893	905	**+1%**
	cow-calf+finishing	819	762	**-7%**
Energy consumption (MJ/100 kg LWP)	cow-calf	2276	1567	**-31%**
	finishing	1397	1350	**-3%**
	cow-calf+finishing	2040	1520	**-25%**
Land use (m2/100 kg LWP)	cow-calf	2951	3325	**+13%**
	finishing	659	527	**+1%**
	cow-calf+finishing	2336	2760	**+18%**

Figure 1: Grassland management and animal production strategies of the two systems

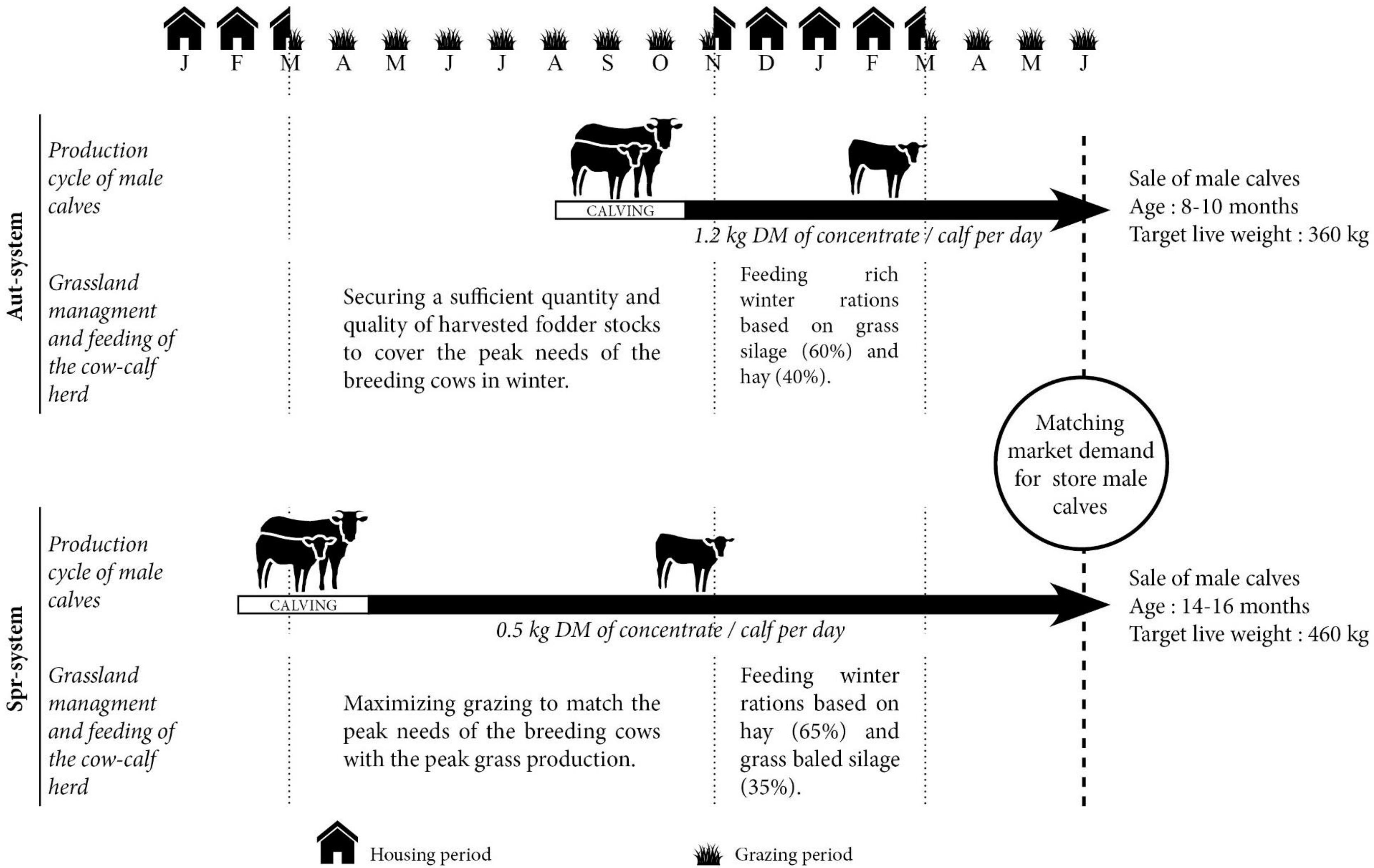
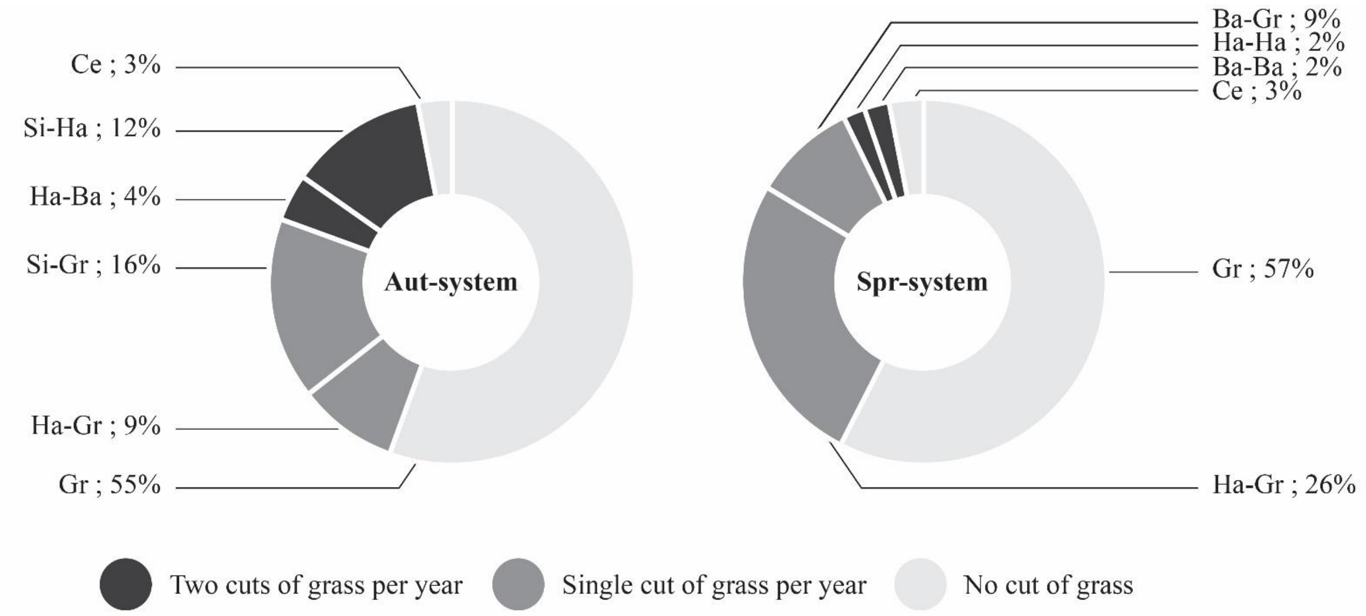
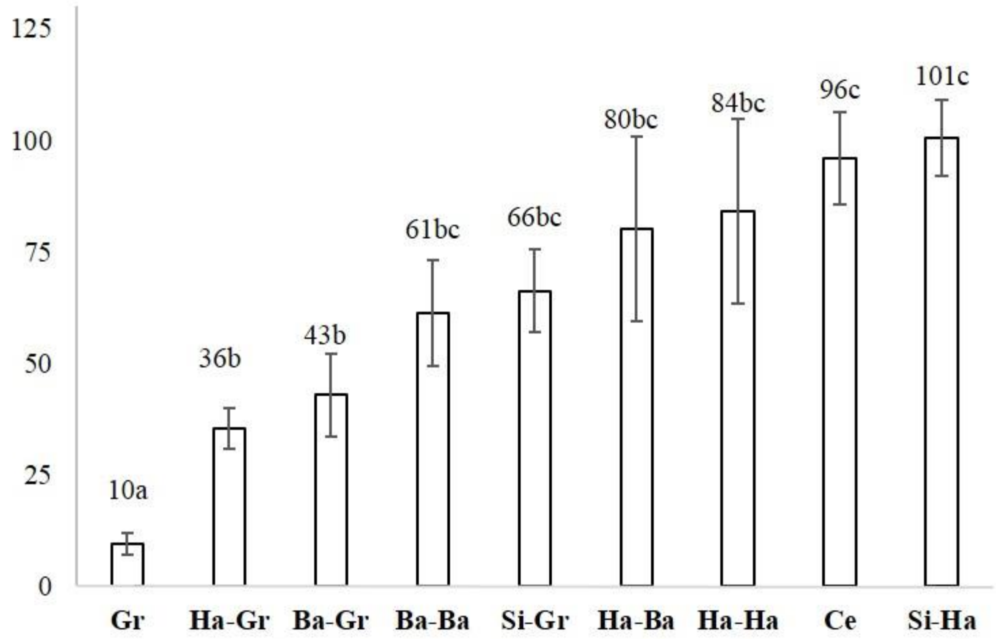


Figure 2: Plot allotment of each system (mean share of the UAA over the two campaigns)



The letters combinations refer to the succession of the following practices on the plots during the production campaign: Gr: grazing; Ha: hay; Si: grass silage; Ba: grass baled silage; Ce: cereal crop.

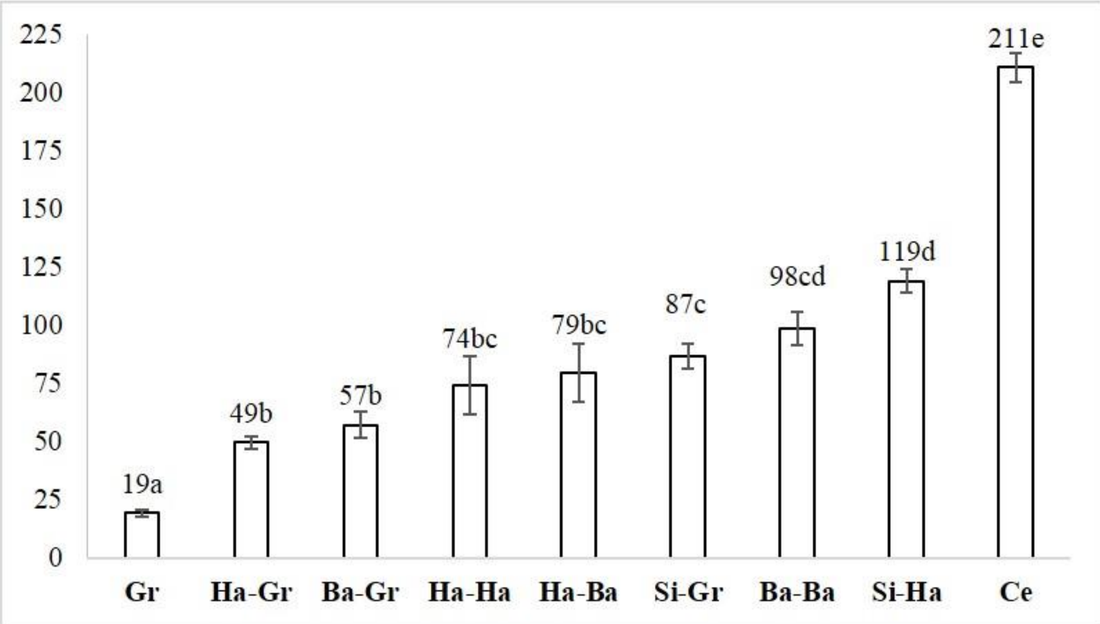
Figure 3: Mineral fertilizer inputs* (kgN/ha) for the different management practices



The letters combinations refer to the succession of the following practices on the plots during the production campaign: Gr: grazing; Ha: hay; Si: grass silage; Ba: grass baled silage; Ce: cereal crop.

**Values expressed as LSmeans and associated SE. Different letters correspond to significative difference ($p<0.05$).*

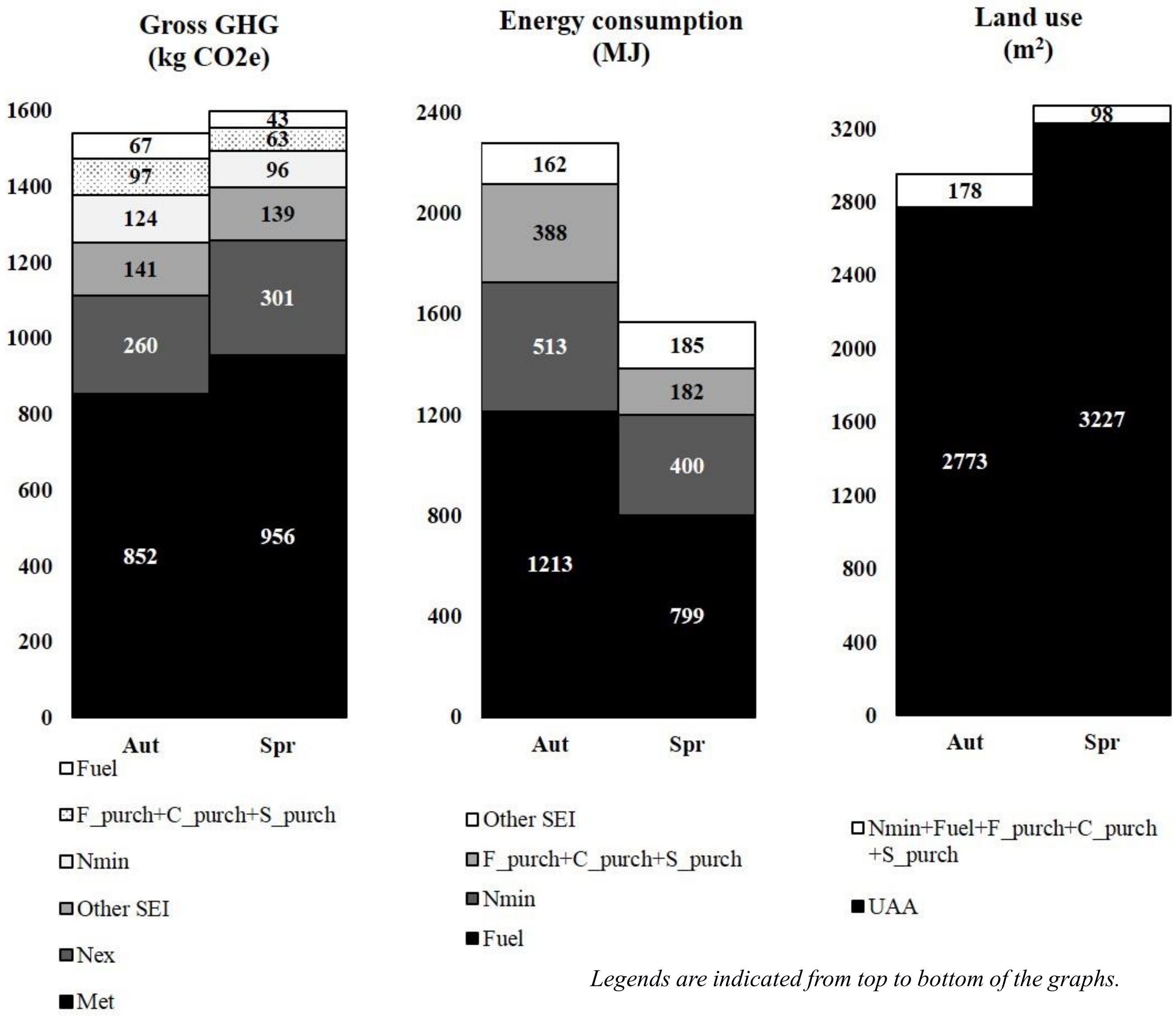
Figure 4: Fuel consumption* for the different management practices (L/ha)



The letters combinations refer to the succession of the following practices on the plots during the production campaign: Gr: grazing; Ha: hay; Si: grass silage; Ba: grass baled silage; Ce: cereal crop

**Values expressed as LSmeans and associated SE. Different letters correspond to significative difference (p<0.05). These values include fuel consumption on the plot and for tractor trips between the plots and the farm's buildings.*

Figure 5: Environmental impacts related to the different SEI in the two systems (/100kg LWP)



Legends are indicated from top to bottom of the graphs.

Figure 6: Offsetting of gross GHG emissions through carbon storage (kg CO_2e / 100 kg LWP)