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Can extensification compensate livestock greenhouse gas emissions? A study of the carbon footprint in Spanish agroforestry systems

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ABSTRACT

Dehesa agroforestry systems (rangelands located in Southwest Spain) are characterised by their semi-arid and often marginal conditions. These features are behind the low supply of pastures available for livestock use, which leads to proper management being based on the use of reduced stocking rates which imply minimal animal pressure on the territory.

In this sense, the study of the role of carbon footprint in extensive systems is of great interest by analysing, within a case study framework, the various production systems available in *dehesa* farms and providing the methodological adjustments required to generate results that are comparable with other livestock systems and species.

Results have revealed that beef farms with fattening calves are those with the lowest carbon footprint levels (8.62 kg of carbon dioxide equivalents (CO_2eq)/kg live weight), followed by meat production sheep farms and farms selling calves at weaning. Enteric fermentation accounts for 64.10%–43.63% of the total emissions, and it is linked to the extensification of these systems and to the grazing diet of the animals. The system's own emissions could reach up to 78% in meat production systems. Undoubtedly, feeding is the input that amounts for the highest percentage of off-farm emissions, as it can reach up to 44.60% of the total emissions in dairy sheep farms and 21.20% in the meat production sheep farms.

Soil sequestration has also been observed to range between 270.02 and 334.01 kg CO_2eq ha^{-1} y^{-1} in the extensive farms under study, which represents considerable carbon compensation. It should be noted that these systems cannot compete in product units with the more intensive ones and, therefore, carbon footprint in *dehesa* agroforestry systems should be referred to the territory.

1. Introduction

One of the challenges the world faces over the next decades is the preservation of its natural resources, at the same time as the production of sufficient food to satisfy the demand of the growing human population (Ibidhi et al., 2017). But with the growing concern about climate change and the already significant contribution of food production to the emission of greenhouse gases (GHG) (Herrero et al., 2013) there can be a need to compensate food production and GHG emissions.

In this context, calculating the Carbon Footprint (CF) of products has become increasingly popular. Carbon Footprint provides an estimate of the total GHG emitted during part or all of the life of a good or service (BSI, 2011), expressed as CO_2eq. It can be used to identify and assess environmental loads associated with a process, product or system, and this assessment allows for the examination of potential bio-physical trade-offs from proposed policies and other measures (Galli, 2015). Carbon Footprint is increasingly used in the food supply chain to determine the quantity of GHG emitted at each stage of the production process, and it may extend to the distribution and usage phases (Jones et al., 2014). Carbon Footprint also enables carbon labelling of products -therefore allowing sustainable consumer purchasing decisions-, and provides an

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emissions' benchmark against which mitigation targets can be set and progress measured.

The major reason for the widespread use of CF in food products is the attention that climate change has received on the global environmental agenda (Röös et al., 2011), as food production significantly contributes to the increasing human input to the GHG emissions. Thus, society has expressed concern about the environmental impacts caused by the growing need for food production to meet the global demand (Florindo et al., 2017).

The growing alarm over the environmental impacts and different characteristics of food has increased consumer interest in the production methods and other attributes of food products (Forsman-Hugg et al., 2008), also spurring a flurry of discussion in the popular media regarding the climate impacts of livestock production and the comparative performance of feedlot and grass-based production systems (Pelletier et al., 2010). Thus, the concerns about reducing GHG emissions to mitigate climate change have recently promoted the assessment of the CF for various activities and products (Luo et al., 2015).

1.1. The importance of using CF in animal production systems

The environmental impacts of agricultural production depend to a great extent on the production systems, which can be influenced by techniques, harvesting period and other technical issues. This primary phase is seen as the main contributor to the environmental impacts of food, related to biodiversity loss, GHG emissions and reduction of soil fertility (Mohamad et al., 2014).

According to the FAO's report "*Livestock's Long Shadow*", the livestock sector is seen as a major contributor to some of the most serious environmental problems at local and global levels (Steinfeld et al., 2006). The livestock sector represents 12% of all human-induced GHG emissions, with the ruminant sector being responsible for 80% of these GHG emissions (Havlik et al., 2014). The report also implies that the livestock sector increasingly competes for scarce resources and causes severe impact on air, water and soil. Since its publication, public and scientific awareness about the impact of animal production on the environment has increased (Steinfeld et al., 2006).

Among livestock food products, meat causes the greatest environmental impact. This is due to the inefficiency of animals to convert feed to meat, as 75–90% of the energy consumed is needed for body maintenance or lost in manure and by-products such as skin and bones (Röös et al., 2013). There are many processes contributing to major GHG emissions during meat production, mainly: (i) production of feed, (ii) enteric fermentation from feed digestion by animals (mainly ruminants), (iii) manure handling and (iv) energy use in animal houses (Steinfeld et al., 2006).

Furthermore, GHG emissions associated with meat production can be effectively reduced through: (i) improvements in animal productivity and fertility; (ii) intensification of production as output/ha (provided that higher input requirements of feed and/or fertilizer are offset by higher levels of productivity); and (iii) soil CO_2 sequestration in grasslands (Beauchemin et al., 2008; Crosson et al., 2011).

Therefore, the analysis of the CF and the variables included in livestock production may identify procedures or techniques in which emissions can be reduced by improving efficiencies (Wiedmann and Minx, 2007). Table 1 shows the CF for various production systems and functional units (FU, the unit selected to express the results of the analysis, e.g. kg of meat or litre of milk produced) and reflects the inherent variability of this indicator.

Strangely enough, at least when it comes to environmental issues, intensifying animal production is generally advocated to mitigate certain environmental impacts, such as the GHG emissions associated with the production of foods of animal origin (Steinfeld and Gerber, 2010). In this regard, the intensification of animal production in feedlots or through changes in their diet allows an early slaughter and has been reported to be a strategy adopted in several countries to reduce GHG emissions in beef production (Ruviaro et al., 2016).

With that in mind, many consumers are still unfamiliar with CF information, which makes it difficult for them to evaluate and compare the different products which are on offer (Kemp et al., 2010). However, meat companies are interested in finding out how different product characteristics can influence consumer choice and whether there is a possibility for a price premium to be added if products are differentiated using the CF attribute (Koistinen et al., 2013). This topic is especially relevant for extensive systems, in which the environmental values associated to livestock production can be overshadowed by the comparatively higher emissions of these production systems, as carbon sequestration by the environment (soil, plants …) is usually not considered.

In this context, the study of the role of CF in extensive systems is of great interest through the analysis -within a case study framework- of the various production systems available in *dehesa* agroforestry systems[1] (Spanish rangelands) and through the provision of the methodological adjustments required to generate results that are comparable with other livestock systems and species.

2. Materials and methods

Among the various methodologies available to estimate the GHG emissions, Life Cycle Assessment (LCA) is an internationally accepted, standardised method used to identify and quantify the environmental impact of a product (Buratti et al., 2017), and it has therefore been selected for this piece of research. Through the entire life cycle of a product, LCA accounts resource consumption, energy, pollutant emissions, etc. (Goldstein et al., 2016).

The calculation of CF has been made in accordance with British Standard PAS 2050 and the IPCC guidelines for national GHG inventories (IPCC, 2006). An adaptation of the methodology quoted by the Spanish Ministry of Agriculture has also been followed regarding the characteristics of livestock in the analysed areas and manure management (MAPA, 2012). The methodological procedure followed in this piece of research consisted of an LCA analysis of the CF taking into account the soil's carbon sequestration.

2.1. Data collection

This study is based on the analysis of four case studies, which were selected as the most representative types of *dehesa* farms. Although global system information may be lost when we deal with technical-economic aspects, the choice of representative farms within a case study analysis allows us to delve more deeply into complex issues (Ripoll-Bosch et al., 2012) such as those related with inventory data collection that are necessary both for LCA and for the calculation of the CF in farms. This methodological choice can be found in other research on CF such as that of Stanley et al. (2018). The analysed farms are described below.

[1] The *dehesa* is an agroforestry system characterized by the presence of a low-density tree layer (30–40 trees/ha, mainly Quercus Ilex and Suber) together with an understorey of pastures, shrubs and crops. The system commonly includes a mixture of different livestock species (beef cattle, sheep, and Iberian pigs), which graze freely and are raised for extensive meat and live animal production. When resources are handled efficiently, the woodland (trees, shrubs, etc.) and the pasturelands provide most of the animal feed needed in the farm. At the same time, livestock grazing avoids shrub invasion and therefore the degradation of the system.

Table 1
Carbon Footprint of various production systems and FUs.

Type of product	Production system	Carbon footprint	Functional unit	References
Sheep/lamb	Pasture-based	25.9	kg CO_2eq/kg lamb live weight	(Ripoll-Bosch et al., 2013)
	Mixed system	24.0	kg CO_2eq/kg lamb live weight	(Ripoll-Bosch et al., 2013)
	Zero-grazing	19.5	kg CO_2eq/kg lamb live weight	(Ripoll-Bosch et al., 2013)
	Lowland farms	10.85	kg CO_2eq/kg lamb live weight	(Jones et al., 2014)
	Upland farms	12.85	kg CO_2eq/kg lamb live weight	(Jones et al., 2014)
	Hill farms	17.86	kg CO_2eq/kg lamb live weight	(Jones et al., 2014)
	Conventional system	17.5	kg CO_2eq/kg lamb meat	(Williams et al., 2006)
	Organic system	10.1	kg CO_2eq/kg lamb meat	(Williams et al., 2006)
	Agro-pastoral system - crop-residues	26.6	kg CO_2eq/kg carcass weight	(Ibidhi et al., 2017)
	Pastoral system using barley	21.1	kg CO_2eq/kg carcass weight	(Ibidhi et al., 2017)
Milk	Semi extensive and local breed	3.8	kg CO_2eq/kg corrected milk	(Batalla et al., 2015)
	Semi intensive and local breed	3.02	kg CO_2eq/kg corrected milk	(Batalla et al., 2015)
	Mixed	1.11	kg CO_2eq/kg corrected milk	(Gollnow et al., 2014)
	Intensive and local breed	2.06	kg CO_2eq/kg corrected milk	(Petersen et al., 2013)
	Extensive and local breed	2.18	kg CO_2eq/kg corrected milk	(Petersen et al., 2013)
	Extensive system in New Zealand	1	kg CO_2eq/kg of energy corrected milk	(Flysjö et al., 2011)
	Intensive system in Sweden	1.16	kg CO_2eq/kg of energy corrected milk	(Flysjö et al., 2011)
Beef	Extensive system	4.8–8.2	kg CO_2eq/kg live weight	(Ogino et al., 2016)
	Intensive system	10.6	kg CO_2eq/kg live weight	(Ogino et al., 2016)
	Extensive (pasture) system	14.0	kg CO_2eq/kg live weight	(Ogino et al., 2016)
	Conventional system	15.5	kg CO_2eq/kg live weight	(Edwards-Jones et al., 2009)
Pork	Conventional system from feed	6.70–8.70	kg CO_2eq/kg live weight	(Noya et al., 2016)
	Conventional system from feed	5.46	kg CO_2eq/kg live weight	(Dolman et al., 2012)
	Conventional system from feed	3.34	kg CO_2eq/kg carcass	(González-García et al., 2015)
Chicken meat	Industrial system	2.6	kg CO_2eq/kg carcass weight	(Ibidhi et al., 2017)
	Conventional production system	2.2	kg CO_2eq/kg carcass weight	(Wiedemann et al., 2017)
	Free range production system	1.8	kg CO_2eq/kg. boneless chicken meat portions	(Wiedemann et al., 2017)

2.1.1. *Extensive meat sheep farm*

This farm is devoted to the breeding and extensive production of meat sheep using the native Merina breed. The holding is located on dry land pastures in the southwest of the Iberian Peninsula. Feeding of adult animals is based on the use of grazing resources provided by the farm. The main outputs of the farm are lambs, which are sold to abattoirs for slaughtering after a production cycle of 85–90 days.

2.1.2. *Extensive beef/calf cattle farm*

This holding corresponds to the traditional beef production from suckler cows raised in the rangelands in the Southwest of the Iberian Peninsula. It is based on the grazing of cows and calves in the *dehesas*, using the available resources of pasture and the woodland pruning waste. The main products obtained are calves sold at weaning age to other farms of feedlots where they are finished. The production cycle lasts approximately 6 months and the final life weight is around 450–550 kg.

2.1.3. *Extensive beef/calf cattle farm with feedlot finishing of calves*

This case is a typical cattle farm in *dehesas* with suckler cows but where the sold animals -calves- have been fed in a feedlot for several months. Although the system is purely extensive, the last phase -the finishing of the calves- has a semi-intensive character. The production cycle is longer than the previous one, as it extends up to 12 months of the calf's life and the animals are sold to abattoirs for slaughtering.

2.1.4. *Grazing dairy sheep farm*

This holding is based on dairy sheep systems but taking advantage of marginal rain-fed grassland areas. In these systems, farms have grazing areas, a differential element compared to other models of dairy sheep production. The management is semi-extensive with the use of natural pastures and supplementation with straw and concentrates. Its main production is milk, while the lambs are just a by-product for the farm.

The data were obtained by monitoring the various farms with field visits and interviews with the farmers being carried out between January and May 2017. The data collected reflect the average state of the farms for the previous year.

2.2. *Definition of system boundaries and functional unit*

System boundaries include all the emissions that are produced within the holding (enteric fermentation, manure management, management of soils …). It also includes the emissions from manufacturing and the transport for each input used in the system —feeding stuffs, consumption of fuel and electricity, etc. Fig. 1 shows the various steps in this LCA study and the system boundaries.

Life Cycle Assessment uses the FU concept to compare various food products. In essence, the FU strives to provide a common basis of comparison between different means of achieving the same end (Owsianiak et al., 2014).

In this paper, the FU is the reference unit with which all the produced emissions of the system will be associated. The FU varies according to the analysed case and uses the main type of production in each system as a reference. In beef and sheep meat systems, the defined FU is the kg of live weight of product, i.e. the kg of live weight of lambs or calves. In dairy sheep systems the FU is a litre of milk. The FU is often based on the mass of the product under study (Cederberg and Mattsson, 2000). Therefore, mass allocation will be used as the method of assignment in this study.

2.3. *Estimation of GHG emissions and calculation of CF level in farms*

There are various methodologies in the literature used in the estimation of GHG emissions and their contribution to the CF level of a product, organisation or service. For the purposes of this study it was decided that the IPCC guidelines for national inventories of GHG (IPCC, 2006) should be used.

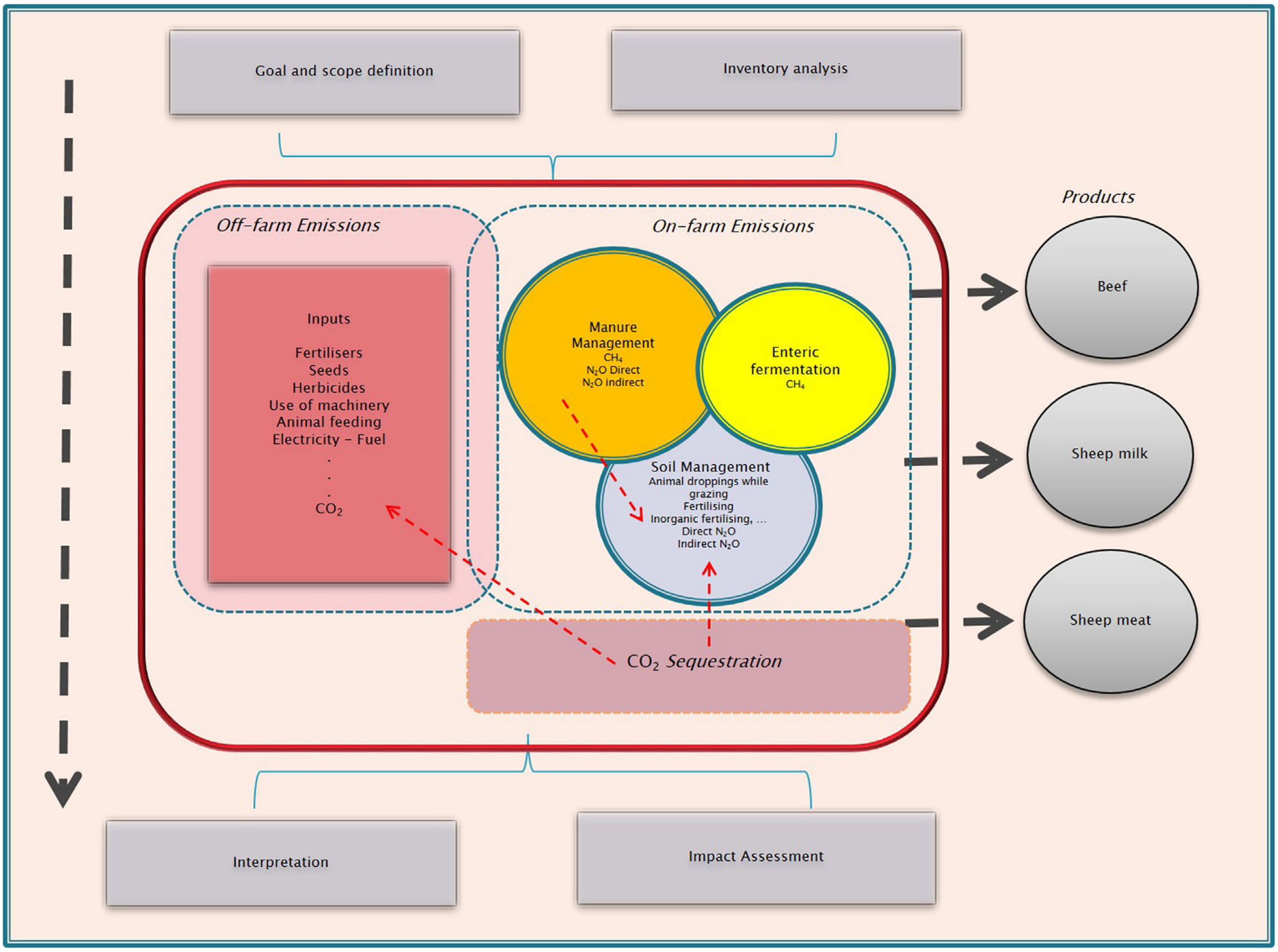

Fig. 1. Stages of LCA and system boundaries.

All emissions are expressed in kg CO_2eq. Thus, it is necessary to use the concept of potential global warming, which is defined as the impact caused by a certain GHG for a period of 100 years. So, global warming potentials proposed by the IPCC (2007) have been used to convert the raw data of methane (CH_4) or nitrous oxide sources (N_2O) emissions. Each gas has a specific value, 1 for CO_2, 25 for CH_4 and 298 for N_2O. In this way, data from raw emissions of CH_4 and N_2O gases are multiplied by 25 and 298, respectively, in order to convert these data to kg CO_2eq.

In order to estimate the emissions, the emission factors of the gases produced by the system, in addition to the inputs shown in Table 2, have been used. These emission factors have been taken from IPCC for most of the farming processes -enteric fermentation, manure and soil management. Local emission factors, adapted to the characteristics of livestock farming in the analysed areas and their manure management, have also been used according to MAPA (2012). Emission factors regarding the derived emissions from the inputs of the livestock systems were obtained from Bochu et al. (2013).

GHG emissions from animal feeding are caused by manufacturing and transport, including raw materials production, processing, packaging, storage and transport from the industry to the farm. The emissions from fossil fuels take into account the generation and combustion emissions. Electricity consumption in the farms derives from the use of lighting in the facilities, the operation of milking systems, the operation of machinery, etc.

2.4. Inclusion of carbon sequestration in LCA. Calculation of compensated CF

Carbon sequestration refers to the changes in the levels of carbon (C) permanently stored in the soil. These changes take place in the soil of farms due to crop residues, grassland and manure. Furthermore, the changes in the land use and the various management practices by the farm can significantly affect C levels in the soil.

In extensive farming systems, carbon sequestration in grasslands can be considered as a mitigation option (Soussana et al., 2010). However, it is not common to take into account carbon sequestration in the LCA. There are various methods that can be used to estimate carbon sequestration: for example, IPCC (2006) estimated the changes in soil C according to inventories and with a 20-year time horizon. For the purposes of this piece of research, it was decided that the balance of net C flows in the livestock-manure-grazing system proposed by Petersen et al. (2013) and later adapted to systems with similar characteristics to those analysed here (Batalla et al., 2015) would be used.

According to Batalla et al. (2015) the main difference between the chosen method and other methods is the use of a 100-year perspective in order to allocate the changes taking place in the soil's C levels. For our purposes it has been estimated that 10% of C added to the soil will be sequestered in a 100-year time horizon (Petersen et al., 2013).

Table 2
Emission factors used to quantify GHG emissions.

Emission and source	Type of GHG	Emission factors	Unit
On-farm			
Enteric fermentation	CH_4	8.64 kg CH_4/per sheep a year[a] 57 kg CH_4/per cow a year	kg CH_4/year
Manure management			
Manure management CH_4	CH_4	0.19–0.37 kg CH_4/per sheep a year[b] 2.23 kg CH_4/per cow a year	kg CH_4/year
Manure management direct N_2O	N_2O	0.005 kg N_2O eN/kg N Solid storage system	kg N_2O/year[c]
Manure management indirect N_2O	N_2O	0.01 kg N_2O eN/volatilized	kg N_2O/year
Soil management			
N from organic fertilizers (compost, manure)	N_2O	0.01 kg N_2O eN (kg N input)-1	kg N_2O/year
N from urine and dung inputs to grazed soils in Sheep	N_2O	0.01 kg N_2O eN (kg N input)-1	kg N_2O/year
N from urine and dung inputs to grazed soils in Cow	N_2O	0.02 kg N_2O eN (kg N input)-1	kg N_2O/year
Indirect emissions Management Soils	N_2O	0.01 kg N_2O eN (kg % N volatilised/leaching)-1	kg N_2O/year
Off-farm			
Concentrates Dairy sheep	CO_2	0.655 kg CO_2eq/kg	kg CO_2eq/year[d]
Concentrates Meat sheep	CO_2	0.512 kg CO_2eq/kg	kg CO_2eq/year[d]
Concentrates Meat cow	CO_2	0.513 kg CO_2eq/kg	kg CO_2eq/year[d]
Electricity	CO_2	0.308 kg CO_2eq/kWh	kg CO_2eq/year[e]
Fuel	CO_2	2.664 kg CO_2eq/litre- Combustion 0.320 kg CO_2eq/litre- upstream	kg CO_2eq/year[d] kg CO_2eq/year[d]

Most of the emission factors have been taken from IPCC Guidelines (IPCC, 2006).
[a] Emission factor adapted to the area (MAPA, 2012).
[b] With average temperature.
[c] N_2OeN*44/28 ¼ N20
[d] Bochu et al. (2013).
[e] MAPAMA (2017).

3. Results

The analysed production systems are defined by their technical characteristics, their products or system outputs and their needs for input procurement. Table 3 includes a list of these parameters in the studied cases.

Table 3 shows how the farms under study correspond to systems ranging from the extensive (meat production) to semi-intensive (milk production). As a common characteristic, they all have animals being raised on grazing to a greater or lesser degree. This proportion of time devoted to grazing decreases in dairy sheep and fattening calves, however it is 100% in meat sheep and in the farms selling calves at weaning age.

Farm sizes range between 150 and 270 ha with stocking rates of 0.30–0.46 LU/ha. Born lambs range from 1.12 in meat systems to 1.20 in dairy sheep. The number of calves born per cow goes from 0.81 to 0.84. Generally, livestock activities are the only economic activity of the farm.

Table 3
Economic and technical indicators of the studied farms.

Indicators	Extensive meat sheep farm	Extensive beef/ calf cattle farm	Extensive beef/calf cattle farm with feedlot finishing of calves	Grazing dairy sheep farm
Type of systems	Extensive	Extensive	Extensive Semi-extensive	Semi-intensive
Pasture area (ha)	270	150	187.5	250
Average annual temperature (ºC)	16	18	20	16
Kg DM pasture/ha	1100	1200	1200	1000
Permanent labour force (No. AWU)	1	1	1	1
Family labour force (No. AWU)	1	0.3	0.5	1
No. of reproductive sheep or cows (average population)	900	50	73	600
Livestock Units/ha	0.46	0.36	0.40	0.30
Lambs born per sheep	1.12	–	–	1.2
Calves born per cow	–	0.81	0.84	–
% Grazing time/year	100	100	100 50 in fattening	60
Other economic activity	No	Yes	No	No
Inputs purchased by the farm				
Total kg Concentrate bought (per sheep or cow/year)	105	417	1495	225
Fodder bought (per sheep or cow/year)	60.71	1221	1595	200
Fuel (litres/year)	520	1168	1830	3000
Electricity (kwh/year)	4200	–	–	6789
Outputs produced by the farm				
Lambs sold/reproductive sheep	1	–	–	0.8
Calves sold/Cow	–	0.74	0.79	–
Average weight of sold lamb/calf	25	220	400/550	22–25
Kg concentrate/lamb or calf	32.62	–	1000/1750	41.96
Milk, litres/reproductive sheep	–	–	–	350
Kg concentrates/litre milk	–	–	–	1.07
Meat, total kg of lamb/calf meat produced	25,300	9020	27,450	–
Milk, total litres produced	–	–	–	210,000

When the inputs of the system are analysed, fodder consumption is seen to become double in dairy sheep farms when compared to meat sheep systems. The resources needed for feeding also increase in beef farms which fatten calves. Fuel consumption is also higher in milk sheep farms because of the operation of milking rooms and the preservation of the milk in refrigerated tanks.

Table 4 includes the contribution of the various GHG in the four analysed systems expressed in kg CO_2eq per FU. It also includes the contribution percentage of the various production processes.

As Table 4 reveals beef farms with fattening calves are those with the lowest CF levels (8.62 kg CO_2eq/kg live weight), followed by meat sheep farms and by farms selling calves at weaning age. Enteric fermentation ranges between 64.10% and 43.63% of the total emissions, and it is linked to the extensification of these systems and to the grazing diet of the animals. The system's own emissions could reach up to 78% in meat production systems.

Undoubtedly, feeding is the element that amounts for the highest percentage of off-farm emissions. It can reach up to 43.84% of the total emissions in dairy sheep farms and 21.20% in the meat sheep farms.

Enteric fermentation and feeding are the factors with the highest variability, with their figures being largely subject to farming systems based or not on grazing, which also affects the final CF level. As shown, farms that need to purchase large quantities of off-farm feed for livestock tend to account for a lower carbon footprint per head taking into consideration the larger number of product units they produce.

Manure and soil management are also an important source of differences in GHG emissions, ranging from 6–9% in sheep farms to 18–20% in beef farms. The higher value for beef farms is in accordance with other results found in extensive beef farms (Stanley et al., 2018), and can be related with the amount of N excreted per species and with the manure management system. It must also be considered that in extensive systems more than 90% of animal droppings are left directly on the soil.

Fig. 2 shows the importance of the GHG emissions levels from the different livestock systems in terms of enteric fermentation, management of manure, soils and off-farm inputs (feeding stuffs, electricity and fuel).

Enteric fermentation has an important role in all the systems under analysis and especially in those with a purely extensive character based on grazing breeding animals. Meat sheep farms are associated to the highest percentage of emissions due to enteric fermentation, followed by beef cattle farms, where calves are sold at weaning age. Emissions from soil management are mainly found in beef cattle farms.

Despite the lower productivity level of the extensive systems with respect to other systems, they have a buffer capacity of CO_2 emissions due to the waste biomass left in the soil. This factor is totally related to the level of pasture production and the land area of the farms. This buffering capacity is also due to the transformation process of N to C owing to the droppings of grazing animals and the applied manure.

Table 5 shows the estimation of carbon sequestration in the farms under analysis. It is based on the use of the carbon balance in the livestock-grazing system proposed by Petersen et al. (2013) and later adapted by Batalla et al. (2015).

Table 5 includes pasture residues (differentiating between above-ground and below-ground contributions) and their transformation into carbon and then into CO_2. The transformation of the soil's organic Nitrogen into CO_2 has also been taken into consideration, whether it is generated during grazing or from the spreading of livestock manure.

The final outcome on Table 5 reflects that an amount between 270.02 and 334.01 kg of CO_2eq/ha are stored each year in the extensive farms under study, which represents considerable carbon

Table 4
Carbon Footprint per functional unit in the systems under analysis.

	Extensive meat sheep farm		Extensive beef/calf cattle farm		Extensive beef/calf cattle farm with feedlot finishing of calves		Grazing dairy sheep farm	
GHG Emissions	kg CO_2eq/kg product	%	kg CO_2eq/kg product	%	kg CO_2eq/kg product	%	kg CO_2eq/l	%
Enteric fermentation CH_4	**9.01**	**64.10**	**8.69**	**48.99**	**3.84**	**44.57**	**0.80**	**43,63**
Manure management								
CH_4	0.25	1.78	0.41	2.32	0.33	3.88	0.02	1,16
Direct N_2O	0.27	1.92	0.21	1.16	0.07	0.87	0.02	1,07
Indirect N_2O	0.10	0.71	0.08	0.43	0.04	0.43	0.01	0,43
Total manure management	**0.64**	**4.55**	**0.69**	**3.91**	**0.45**	**5.18**	**0.05**	**2,66**
Soil management								
Direct N_2O soil	1.09	7.73	3.23	18.21	1.45	16.80	0.10	5,16
Indirect N_2O soil	0.22	1.54	0.32	1.81	0.14	1.68	0.02	1,03
Total soil management	**1.32**	**9.39**	**3.55**	**20.02**	**1.59**	**18.48**	**0.11**	**6,19**
Total On-Farm Emissions	**10.97**	**78.04**	**12.93**	**72.92**	**5.88**	**68.23**	**0.97**	**52,48**
Feeding								
Fodder for sheep	2.12	15.08	–	–	–	–	0.70	38,04
Fodder for lambs	0.66	4.70	–	–	–	–	0.05	2,71
Silage for cows	–	–	–	–	0.38	4.38	–	–
Fodder for cows	–	–	2.87	16.20	–	–	–	–
Fodder for calves	–	–	0.80	4.50	2.11	24.48	0.00	0,00
Straw	0.08	0.57	0.75	4.20	0.05	0.61	0.00	0,00
Hay	0.12	0.85	0.00	0.00	0.00	0.00	0.06	3,10
Total Feeding	**2.98**	**21.20**	**4.42**	**24.90**	**2.54**	**29.47**	**0.81**	**43,84**
Electricity	**0.05**	**0.36**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**1,75**
Fuel								
Burning	0.05	0.36	0.34	1.94	0.18	2.06	0.03	1,72
Production	0.01	0.04	0.04	0.23	0.02	0.25	0.00	**0,21**
Total Fuel	**0.06**	**0.40**	**0.39**	**2.18**	**0.20**	**2.31**	**0.04**	**1,92**
Total Off-farm Emissions	**3.09**	**21.96**	**4.80**	**27.08**	**2.74**	**31.77**	**0.85**	**47.52**
TOTAL CF kg CO_2eq/FU	**14.06**	**100.00**	**17.74**	**100.00**	**8.62**	**100.00**	**1.84**	100,00
Total kg CO_2eq	**357,321**	–	**159,991**	–	**236,585**	–	**425,036**	–
Total kg CO_2eq per ha	1319.03	–	1066.61	–	1265.16	–	1700	–

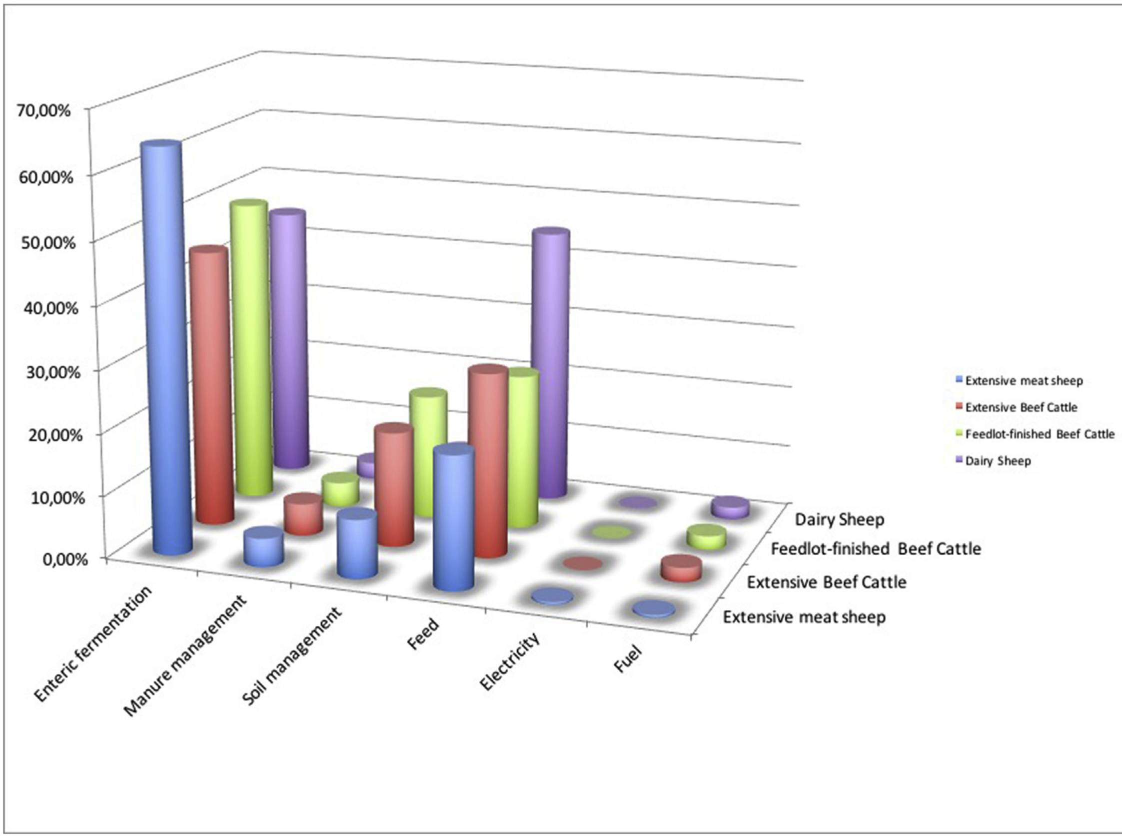

Fig. 2. Importance of the GHG emission levels by type of farm.

Table 5
Carbon sequestration (kg CO_2eq/year) per farm.

CO2 stored	Extensive meat sheep farm	Extensive beef/ calf cattle farm	Extensive beef/calf cattle farm with feedlot finishing of calves	Grazing dairy sheep farm
C from pasture residues				
Pasture residues (kg DM)[a]	451,440	273,600	342,000	380,000
Above ground kg C	53,460	32,400	40,500	45,000
Below ground kg C[b]	149,688	90,720	113,400	126,000
Total kg CO_2eq pasture	**744,876**	**449,973**	**564,300**	**627,000**
C from organic N (manure and grazing)				
kg N excreted	9011.35	3833.96	5339.34	4872.43
kg C from applied manure	9197.5	1246.05	3050.44	4254.86
kg C during grazing	20,085.84	11,214.32	13,852.38	11,589.53
Total kg CO_2eq manure-soil[c]	**107,372.09**	**45,688.02**	**61,977.00**	**58,063.12**
Total kg CO_2eq per farm	852,248.00	511,950.00	636,277	685,063.12
Total kg CO_2eq manure-soil/ha	397.67	304.59	331.42	232.25
Total kg CO_2eq/ha	3156.47	3304.41	3340.14	2740.25
Total CO_2 sequestration (kg CO_2eq ha^{-1} year^{-1})[d]	**315.64**	**330.44**	**334.01**	**270.02**

[a] It has been estimated that pasture residues account for 40% of the total production of pasture, with a C content of 45%.
[b] According to (IPCC, 2006) the default expansion factor for below-ground biomass in semi-arid pasturelands is 2.8.
[c] The conversion factor for N to C is 13/4 and 44/12 for C to CO2.
[d] Annual C sequestration of 10% is considered.

compensation. Finally, Fig. 3 shows the compensated CF per FU. Positive values in Fig. 3 represent the farms' emissions in kg of CO_2eq per FU, while the negative values reflect the annual carbon sequestration in these systems -also in kg of CO_2eq per FU-. Carbon sequestration is proven to be greater in extensive systems than in the semi-intensive ones.

4. Discussion

Livestock production is considered to be responsible for a significant impact on the environment, especially regarding GHG emissions. However, not all livestock production systems generate the same level of pollution, as extensive systems —such as the Spanish *dehesas*- have a territorial component which compensates emissions with biological factors (soil, pasture, trees …) (Moreno and Pulido, 2009).

Although intensive production systems have been found to be more efficient economically than extensive production systems (Horrillo et al., 2016), intensive livestock production is widely regarded by consumers as having a more harmful impact on the

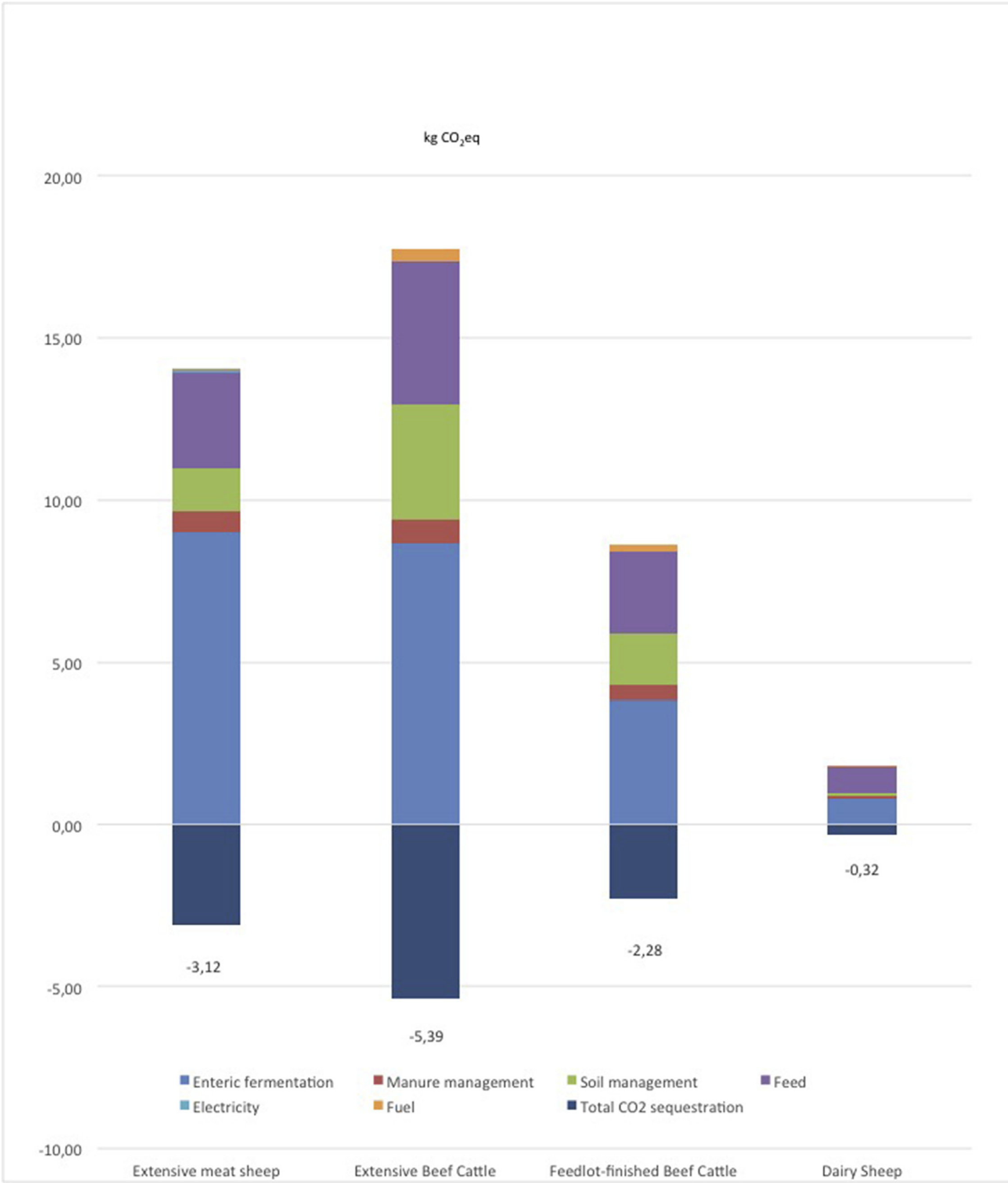

Fig. 3. Compensated CF per functional unit (kg of CO_2eq per FU).

environment. This is due to the livestock supply chain requiring significant resources in terms of feed, energy and water, the production of CH_4, NH_3 and other emissions to the air, together with pollution risks arising from inefficient waste management practices. However, the global warming potential shows that the higher the intensification of production, the lower the CO_2eq per kg of product.

In this context, CF and LCA have become common tools to assess the environmental impact of livestock systems, although this approach reveals some methodological weaknesses which can lead to inaccurate results. In this paper, LCA methodology has been followed as a basis for CF evaluation (McAuliffe et al., 2016). Nevertheless, the lack of consensus on a method selection -system boundaries, functional units, allocation approaches- and the assumptions under consideration hinder the feasibility of a comparative analysis against other studies (de Vries and de Boer, 2010; Edwards-Jones et al., 2009). Besides methodological differences, variability in results also reflects differences in animal productive systems, geographical locations and market conditions.

In this study, the main areas of production (cattle and sheep) found in *dehesa* agroforestry systems have been analysed regarding their CF. A clear relationship between intensification and lower CF per product unit has been identified, a result which is in agreement with previous studies such as those of Batalla et al. (2015) or Buratti et al. (2017).

Regarding the CF in beef production systems, this is one of the most widely discussed environmental issues within the current agricultural community, due to its association with climate change.

In beef production, the total emissions -per kg of live weight- of an animal slaughtered with 430 kg live weight ranged between 18.30 kg CO_2eq (502 days production cycle and intensive system) and 42.60 kg CO_2eq (840 days production cycle and extensive system) (Ruviaro et al., 2015). The results of this research are outside this range of values, as the CF of the beef farms under analysis varied from 8.62 kg CO_2eq (semi-extensive) to 17.74 kg CO_2eq (extensive), although the production cycles in *dehesa* farms are shorter. In accordance to the above-mentioned results, organic beef systems -usually more extensive than conventional due to regulatory constraints- have been found to produce more GHG emissions (24.62 kg CO_2eq/kg live weight) than conventional ones (18.21 kg CO_2eq/kg live weight) (Buratti et al., 2017).

Sheep farming systems in Spain are generally pasture-based and extensive, although large differences in off-farm inputs utilisation, land use and intensification level exist. As a result, the GHG emissions of these systems varied between 19.5 and 25.9 kg CO_2eq per kg of lamb live weight in Northern Spain (Ripoll-Bosch et al., 2013) and 12.48–25.97 kg CO_2eq per kg of lamb live weight in Andalusian *dehesas* (Batalla et al., 2014), with the later figures being similar to those obtained in our study, on account of the similarity of the systems.

There are also numerous studies dealing with the measurement of CF in dairy products. One of these studies was reported by Flysjö et al. (2014) who presented a model to calculate the farm-to-customer CF for different dairy products. The results from that study showed that the largest share of CF of dairy products is produced at farm level. In this context, CF in dairy sheep farms varies from 2.02 kg CO_2eq/litre of milk in semi-intensive farms to 5.17 kg CO_2eq/litre of milk in semi-extensive farms (Batalla et al., 2015). Such figures are in line with those obtained in our study, where semi-intensive farms produce 1.84 kg CO_2eq/litre of milk.

In ruminants, CH_4 production depends on animal type and size, and on feed intake and its digestibility. Emissions of CH_4 decreases as feed digestibility increases (Beauchemin et al., 2008). As intensive systems generally rely more on highly-digestible concentrates, a decrease is expected in CH_4 emissions when intensification level increases (Gerber et al., 2011). The findings of our study are in line with this argument, as CH_4 in extensive meat sheep farms is 64.1% while in dairy sheep the figure goes up to 43.63%. In this sense, improving the quality of feed and the general efficiency of the use of nutrients in the diets are effective practices to reduce the GHG emissions per unit of animal product.

When soil sequestration is considered, CF in extensive production improves and reaches lower values than those of intensive farms. In this context, the compensated CF –including carbon sequestration- in our study has been reduced by 20–30% as compared to the baseline figures, with a higher reduction on those systems more linked to the territory.

Trees play a central role in the carbon cycle and therefore the quantification of the balance between carbon emission and carbon sequestration is one of the main challenges if carbon sequestration is to become a management objective of *dehesa* agroforestry systems (Montero et al., 2005). Although carbon stocks in *dehesa* areas are currently known, no information on annual sequestration due to the tree layer is available. Therefore, this aspect has not been considered in this paper even though it should be taken into account as one of the objectives of future research.

Nevertheless, some estimations can be done for the period of maximum tree growth (100 years) from data of Howlett et al. (2011) and Ruiz-Peinado et al. (2013) for soils and vegetation, respectively. Assuming a temporal frame of 100 years to explain the differences between soil C beneath trees and in open grasslands, carbon sequestration for soils can be estimated at 48.1 kg C ha^{-1} y^{-1} for a typical *dehesa* with 35 trees per ha and canopies 10 m in diameter (27.5% of canopy cover). Carbon accumulated in these trees in the same 100 years can be estimated at 300 kg C ha^{-1} y^{-1}. Overall, carbon sequestration is estimated in the order of 350 kg C ha^{-1} y^{-1}. Indeed, the above-mentioned values fall into the lower part of the range reported by Nair et al. (2009) for agroforestry systems (290–15,210 kg C ha^{-1} y^{-1}).

Apart from the above mentioned role of trees in extensive *dehesa* systems, another important challenge is the accurate adjustment of the emissions due to extensive cattle ranching. In this sense, if pasture was not consumed by livestock it could be thought that the emissions due to rotting vegetation and to the microbial flora of the soil would increase. Therefore, in an adjusted system of emissions, these should be discounted from those of livestock. Accordingly, the level of respiration of the ecosystems, and the increase of CO_2 storage associated with grazing have been studied by Gomez-Casanovas et al. (2018).

The fact that the estimation of carbon sequestration has followed a conservative approach with a time horizon of 100 years, as opposed to the one proposed by IPCC -20 years- (IPCC, 2006; Petersen et al., 2013) must be taken into consideration. Similarly, the CF figures found would have also been substantially higher if the proposal developed by Vleeshouwers and Verhagen (2002) had been applied, as the emissions they found for grasslands were 1.907 kg CO2eq ha^{-1} y^{-1}.

5. Conclusions

Life Cycle Assessment is a useful tool for measuring the potential environmental performance of livestock production. LCA may be combined with other methods to assess economic sustainability of animal production in order to reveal on-farm efficiencies. It also could help to reduce both environmental and monetary costs associated with animal rearing.

The clear definition of LCA models is essential for a comprehensive and detailed assessment of the environmental burden associated with the production of food products. This clarification is important especially when results of LCA studies are used to define policies and initiatives aiming at reducing the environmental impact of animal production systems and to achieve sustainable food supply. According to this study, there is a need to develop a common framework to assess CF in order to reinforce the reliability of LCA as a decision-support tool.

Direct comparison between the production systems is very difficult due to the optimised nature of commercial livestock rearing and the difference amongst the functional units used in the systems. However, and likewise other studies, a clear and inverse relationship between intensification and CF per product unit has been found. This is due to the higher efficiency of intensive production systems, which implies that each unit produced in an intensive farm requires less inputs than its equivalent in an extensive holding.

However, extensive farms usually have a territorial component (hectares of agricultural land, with pastures, trees …) which can help to compensate for CO_2 emissions, due to C sequestration. Nevertheless, it is not common to take into account carbon sequestration in LCA studies, which creates a disadvantage for extensive systems and can send confusing messages to the consumers and endanger the persistence of these valuable and complex systems.

Acknowledgments

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