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Environmental performance of sorghum, barley and oat silage production for livestock feed using life cycle assessment

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ABSTRACT

The role of environmental consequences derived from cereal production in agricultural systems is widely recognised. Life Cycle Assessment (LCA) has been considered as a useful tool to support environmental decision-making in agricultural systems. In this study, the quantification and identification of the environmental impacts derived from two different double cropping systems comprising winter and summer crops for silage production (forage sorghum, barley and oat) was performed following an attributional LCA perspective in accordance with ISO 14040 standards. Primary data of cereal production for dairy cattle feeding were obtained from a representative year. Only secondary data were used for background processes.

Four different functional units were considered to report the environmental profiles: 1 t dry matter silage (base case), 1 ha, 1 t crude protein and 1 MJ metabolisable energy. According to the results, the combination of sorghum with barley presented better environmental results than sorghum with oat when the impacts were reported for mass and energy based functional units, which is attributed to the biomass yield (23% higher) achieved under similar agricultural practices. When the functional unit of 1 ha was taken, the scenario of sorghum and oat was more beneficial due to lower requirements of diesel and herbicides for the agricultural activities per cultivation area. Regardless the functional unit considered, both field preparation and biomass harvesting were the agricultural stages which reported the largest contributions to the environmental impacts (~99%) due to on-field emissions associated to manure application, diesel use in agricultural machinery and seed production.

If the crops are separately assessed, sorghum cultivation system would be the best option due to the highest biomass yield, followed by barley and oat considering 1 kg dry matter silage as functional unit. However, when 1 ha was considered to report the results, the barley system was the worst alternative due to the highest seed ratio and diesel requirements (high input-output system).

Environmental results must be interpreted within limitation of assumptions accepted by LCA community. Variations on climate and soil parameters as well as nutrients uptake by crops should be analysed and required in further research in order to reduce uncertainties.

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1. Introduction

The growing demand all over the world for feed and food, the increasing economic and political relevance of this sector as well as the emergent concern over environmental sustainability, have attracted the attention of policy makers to provide guidelines and regulate production schemes under sustainability criteria (Sandars et al., 2003; Cellura et al., 2012; Ruviaro et al., 2012). These considerations together with the current consumption patterns have involved an increasing interest towards the communication of the environmental profiles of food and feed products (Cellura et al., 2012).

The agricultural sector plays a significant role in a huge range of environmental impact categories such as eutrophication, acidification, land use and climate change. In fact, the agricultural production sector is responsible for 14% of the total global anthropogenic greenhouse gases (GHG) emission taking into account CH_4 emissions from enteric fermentation, N_2O from soils as well as emissions from biomass burning, rice production, manure management and land cover change (US-EPA, 2006; Barker et al., 2016; Roer et al., 2012).

Agricultural systems are dependent on inputs such as land, fertilisers, fossil fuels, machines, pesticides and electricity (Da Silva et al., 2010; Martínez-Blanco et al., 2009; Noya et al., 2015). The

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environmental impacts derived from agricultural systems mainly rely on the fertilising process (e.g. N and P emissions derived from fertiliser production and application) and the use of fossil fuels in agricultural machinery (Charles et al., 2006; Martínez-Blanco et al., 2009; González-García et al., 2012; Bacenetti et al., 2014; Noya et al., 2015). However, agricultural related activities are highly diversified all over the world either in cultural or biophysical terms. Consequently, the application of a standardised methodology to assess the environmental burdens of local production systems may be complex and even controversial.

Sustainable Production and Consumption policies are being developed by European Commission (Freibauer et al., 2011) in order to promote the environmental assessment of food and feed products, paying attention on their production chains. Life Cycle Assessment (LCA) methodology (ISO 14040, 2006) has received special attention in order to analyse the environmental profiles derived from different production sectors including agriculture (Charles et al., 2006; González-García et al., 2010, 2012; Cellura et al., 2012; Bacenetti et al., 2014), being considered the methodological vertebral column of sustainable production (Cellura et al., 2012). This methodology allows determining environmental impacts taking into account all the related processes or activities involved throughout its life cycle. Moreover, other available organization specific tools based on the life cycle perspective, such as Environmental Management Systems and Environmental Products Declaration, can help food and feed producers to disseminate environmental information from their products to consumers. However, although LCA is being more and more important in environmental evaluations, this tool quantifies potential impacts although with certain limitations. In this sense, assumptions and a degree of uncertainty are inherent as with any complex model. An accurate LCA study requires managing good quality, representative and real data. Otherwise, the quantification of the environmental impacts may be underestimated (ISO 14040, 2006).

LCA methodology can be used as a decision tool for a number of applications: i) to identify critical points of a production system, 2) to propose improvement alternatives to minimise the environmental burdens and, 3) to identify differences among systems with equivalent functions (Beccali et al., 2009; Benglini and Busto, 2009). Crops cultivated under very different management schemes (e.g. conventional vs organic farming, single vs rotation systems) have been assessed with the aim of identifying strengths and weaknesses from an environmental point of view since different yields, tillage levels, agrochemicals and production costs can be identified (Dalgaard et al., 2001; de Ponti et al., 2012; Fedele et al., 2014).

Numerous LCA studies on agricultural products (cereals, fruits, vegetables and forage crops) have been carried out so far where very different systems have been environmentally evaluated. Food products such as apple (Milà i Canals et al., 2006; Strapatsa et al., 2006; Soler-Rovira and Soler-Rovira, 2008; Cerutti et al., 2013), nectarine (Cerutti et al., 2010), strawberry (Williams et al., 2008), rice (Blengini and Busto, 2009; Fusi et al., 2014), melon, pepper or tomato (Martínez-Blanco et al., 2009; Cellura et al., 2012) have been evaluated from a holistic environmental perspective.

According to the literature (Hospido et al., 2003; Castanheira et al., 2010; Nguyen et al., 2010, 2011; Gollnow et al., 2014; González-García et al., 2015; Mogensen et al., 2014; Pirlo et al., 2014; Ruviaro et al., 2012), the environmental profiles related with livestock sector (e.g. dairy cattle and pig farms) are considerably affected by the production of animal feed. In fact, GHG emissions derived from feed production is one of the *hotspots* in livestock production (Mogensen et al., 2014). Furthermore, animal feed production represents nearly 80% of the total agricultural area (Mogensen et al., 2014). Livestock feed typically consists of fodder crops such as maize silage, barley, alfalfa, oat and wheat straw or ryegrass (Hospido et al., 2003; Castanheira et al., 2010; Mogensen et al., 2014). A comprehensive assessment of the agricultural practices required for animal feed production and their corresponding environmental impacts is essential. The production of ensilages can be carried out mainly under two different crop management regimes (Hu et al., 2013; Bacenetti et al., 2014; Wang et al., 2014): single cropping system or double cropping system with winter cereals (wheat, barley, oat) followed by summer crops (maize, sorghum). Double cropping or rotation systems must be carefully evaluated because they require higher production costs, field operations and agrochemicals for increasing production yields in comparison with single cropping systems (Bacenetti et al., 2014). Moreover, the selection of double cropping systems is also related with the climatic conditions. It is important to remark that both barley and oat are the most important cereals after wheat, in terms of cultivated area in temperate regions (Fletcher et al., 2009) mainly because they are used for both human consumption and animal feed, as either grain or whole crop silage.

Wheat (Brentrup et al., 2004; Charles et al., 2006; Wang et al., 2014; Noya et al., 2015), alfalfa (Gallego et al., 2011), soybean (Baumgartner et al., 2008; Da Silva et al., 2010; Fedele et al., 2014), triticale (Noya et al., 2015) and maize (Wang et al., 2014; Noya et al., 2015) are examples of feed products environmentally analysed and available in the literature.

The objective of this research is to evaluate the life cycle environmental profile of three different fodder crops widely cultivated in Spain under double cropping systems in order to produce feed for dairy cows. To do so, a representative dairy farm has been assessed in detail. Up to date, there is no available study in the literature reporting environmental impacts derived from the cultivation of feed crops in Spain although this country occupies the fourth position in Europe in terms of cereal production (Eurostat, 2015). The crops under assessment are: barley, oat and forage sorghum, which are currently cultivated in a double cropping regime. Thus, two different scenarios have been proposed and compared: a) the combination of forage sorghum (summer crop) and barley (winter crop) and b) the combination of forage sorghum and oat (winter crop). Because different functional units can lead to different results for the same production system, specifically in agricultural systems, four functional units have been adopted in order to get a more complete understanding of the environmental profiles.

2. Materials and methods

LCA is a quantitative procedure to evaluate the environmental loads associated with a production chain and to identify opportunities to achieve environmental advantages. With this objective, a LCA study identifies the consumption of natural resources and the emissions to environmental compartments throughout the life cycle of the production chain (ISO 14040, 2006). The LCA methodology following the principles of the ISO standards was used to evaluate the production of forage sorghum, oat and barley from an attributional perspective (ISO 14040, 2006).

2.1. Goal and scope of this study

The main goal of this study was to evaluate the environmental performance of three fodder crops typically used for dairy cattle feed in Spain and commonly cultivated in double cropping systems. The cropping systems were assessed from a cradle-to-gate approach. Thus, the further processing of each crop into animal feed was excluded from the system boundaries. Moreover, the most critical stages or processes (environmental *hotspots*) throughout the life cycle were identified as well as the cultivation system with higher environmental benefits. In order to study the impacts of these Spanish fodder crops, two agricultural scenarios based on records from a representative farm located in Calldetenes (Catalonia, NE Spain) were considered. The farm under assessment is located in one of the Spanish regions with the largest livestock production areas, with a large density of farms (≈21% of total), husbandry activity and related industries such as slaughterhouses, food industries and sub-suppliers as well as with the largest milk production ratios (≈21% of total) (GenCat, 2010). The characteristics of the farm (with near of 1200 heads) and farming practices are common to dairy farms from Northeast Spain. The total area of the farm is 74.7 ha, of which 55.27 ha are used for cereals cultivation and have been analysed in this study. Agricultural activities were evaluated for a period of five years (2009–2014) in order to obtain consistent and representative results.

2.2. Functional units

The functional unit (FU) is the basis for comparisons between different systems in LCA (ISO 14040, 2006). The definition of the FU could be considered straightforward although, especially in agricultural systems, it is not always right. The appropriate selection is of major importance since different FUs can lead to very different results and conclusions (Martínez-Blanco et al., 2009). In this study, it was considered 1 t dry matter (DM) of silage for cattle feed production as base unit for comparisons, which is in agreement with other related studies (Charles and Nemecek, 2002; Blengini and Busto, 2009; Roer et al., 2012; Mogensen et al., 2014). According to Cerutti et al. (2010), a mass based FU is easy to comprehend although it considers efficiency but not sustainability as well as quality. Therefore, other three alternative FUs were taken into account for discussion: area occupied (1 ha), crude protein content (1 t protein) and the metabolisable energy content (1 MJ) from the total digestible nutrients and crude protein present in the silage (DiCostanzo, 2015). The concern of a land based unit is considered complementary to the mass based unit since both of them usually lead to different results. The impacts are related to a specific amount of land however, it is not frequently used since land use is not directly a service and does not provide productive functions (Cerutti et al., 2010). Specifically, when crops under assessment are focused on the production of animal feed, the crude protein content and the metabolisable energy content could be considered as alternative interesting references to report the environmental results since both units account the quality of the product (Martínez-Blanco et al., 2009). Table 1 depicts the average biomass yield and composition of each fodder crop analysed directly supplied by farmers.

2.3. Description of the fodder cropping systems under study

The species under study are fodder crops used in Spain for animal feeding: barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.) and forage sorghum (*Sorghum* spp.). All cultivations are located in Calldetenes (Catalonia, NE Spain) and managed by a representative dairy farm. The climate in this area is warm and temperate (average annual temperature is 13.5 °C). The farm has 55.27 ha of arable land, exclusively dedicated to forage sorghum from June to November, barley (38%) from November to June and oat from February to June (62%). According to the two rotation regimes, two double cropping scenarios can be identified:

Scenario A (21 ha): forage sorghum (summer crop) followed by barley (winter crop) (Fig. 1a).

Scenario B (34.27 ha): forage sorghum followed by oat (winter crop) (Fig. 1b).

These double cropping systems dedicated to the production of animal feed have been divided in three main stages or phases: field preparation (S1), crop growth (S2) and biomass harvesting (S3). All these stages included different agricultural activities (Fig. 1) and both cropping systems differ in terms of land occupation time per year. In this sense, Scenario A implies a period of 12 months while land occupation in Scenario B is shorter: 10 months.

The life cycle assessment of each scenario comprised raw materials extraction (e.g. fossil fuels and minerals), manufacture (e.g. seeds, fertilisers, pesticides and agricultural machinery), use (tailpipe emissions and tyre abrasion emissions), maintenance and final disposal of machines as well as supply of agrochemicals to the farm (e.g. fertilisers and herbicides). Moreover, direct emissions from fertiliser handling and management (CH_4, N_2O, N2, NO_x, NH_3, $NO_3{}^-$ and $PO_4{}^{-3}$ leaching) were also included within the system boundaries. Thus, an input/output analysis of each agricultural activity or operation was carried out in detail. The agronomic inputs required in each crop growth are displayed in Tables 2 and 3 where the features of specific agricultural machine used for these crops are summarised. Farm management activities were performed as recommended by the advisory services of the region.

2.3.1. Scenario A: forage sorghum + barley

Forage sorghum, both grain and forage, is an important feedstuff for livestock. It is a summer crop, commonly in warm climates all over the world, especially where maize cannot be cultivated due to its high water requirements. In June, field preparation starts with the fertilisation with cattle slurry at a rate of 170 kg N ha^{-1} (~57.9 m^3 ha^{-1}) and ploughing. Thereafter, the seeds bed is prepared at a rate of 40 kg seed ha^{-1}. The weed control process takes place by means of 1.2 L MCPA ha^{-1} in July. There is no more agricultural activities (neither irrigation) until November. The whole crop (straw and grain) is harvested and chopped with a self-propelled forage harvester. In parallel, the chopped biomass is loaded into farm trailers coupled to tractors. Finally, the chopped biomass is ensilaged with a wheel tractor equipped with a frontal loader for further storage.

Barley is a winter crop that can be used for animal feeding (grain or fodder). It is one of the most widespread winter crops together with wheat (Bacenetti et al., 2014). Just after the harvesting of forage sorghum, field preparation starts with the addition of cattle manure as organic fertiliser (170 kg N ha^{-1}) followed by ploughing and seed sowing at a rate of 162 kg seeds·ha^{-1}. All these activities are performed in November. Similarly to sorghum cultivation, there is only one weed control in March during the crop growing stage, which consists on the application of 1.5 L ha^{-1} of an herbicide mixture based on Dicamba (10%w/v), MCPA (26.5% w/v) and 2,4-dichlorophenoxyacetic acid. Finally, the biomass harvesting takes place in June. The biomass is chopped, ensiled and stored similarly to sorghum cultivation. A detailed description of operation hours and machinery used per activity is reported in Table 2.

2.3.2. Scenario B: forage sorghum + oat

The cultivation scheme of forage sorghum is exactly the same as in Scenario A. In contrast to barley, cultivation of oat starts in February and it is harvested in June. Consequently, no activities are performed between November and February. Oat is also a winter crop, destined not only for livestock feed but also for human consumption (oatmeal). Oat is normally cultivated in temperate regions and it has a greater tolerance of rain in comparison with other cereals such as wheat (Kim, 2013).

Field preparation related activities start in February when an organic fertilisation with cattle manure is performed (170 kg N ha^{-1}), followed by ploughing and seed sowing with a rate of 108 kg seeds ha^{-1}. In contrast to the other crops under assessment, there is no weed control during crop growth. Thus, from February till June, there is no input in the cropping system. As in barley cultivation, the total biomass is harvested, chopped and ensiled.

Table 1
Silage potential production for the different cropping systems under assessment.

Scenario	Crop	Yield (t_{DM} ha^{-1})	Annual yield (t_{DM})	Crude protein (%)	TDN (%)	ME (MJ kg$_{DM}$$^{-1}$)
A	Sorghum	12.75	267.75	10.5	68.4	11.9
	Barley	7.48	157.08	12.5	53.0	9.2
		20.23	424.83			
B	Sorghum	12.75	436.94	10.5	68.4	11.9
	Oat	3.75	128.51	14.1	49.0	8.4
		16.50	565.45			

t_{DM}—ton dry matter; TDN—Total digestible nutrients (in%); ME—metabolisable energy.

Table 2
Field operations timeline and inventory data (per ha) for the cultivation of sorghum and barley (21 ha) under a double cropping system.

			Tractor (A)		Operative implement (B)		A + B		
Stage	Activity	Time (month)	Weight (kg)	Power (kW)	Type	Weight (kg)	Effective work capacity (ha h^{-1})	Fuel diesel consumption (L h^{-1})	Input rates
Sorghum cultivation									
Field preparation	Organic fertilisation	June	7000	150	Manure spreader	30000	1.0	18	170 kg N ha^{-1} Cattle slurry[a]
	Ploughing	June	5000	135	Ploughshare	1000	0.5	25	–
	Sowing	June	7000	150	Seeder	700	1.0	20	40 kg seeds ha^{-1}
Crop growth	Weed control	July	4000	75	Spraying machine	500	1.5	10	1.2 L ha^{-1} MCPA
Biomass harvesting	Harvesting	November	–	522	Forage harvester	10000	1.0	120	–
	Transport	November	7000	112	Farm trailers	2000	4 × 1.0	20	–
	Ensilaging	November	5050	90	Frontal loader	450	4.0	11.5	–
Barley cultivation									
Field preparation	Organic fertilisation	November	7000	150	Manure spreader	30000	0.3	18	170 kg N ha^{-1} Cattle slurry[a]
	Ploughing	November	5000	135	Ploughshare	1000	0.5	25	–
	Sowing	November	5000	135	Seeder	600	1.0	20	162 kg seeds ha^{-1}
Crop growth	Weed control	March	4000	75	Spraying machine	500	1.5	10	1.5 L ha^{-1} herbicide[b]
Biomass harvesting	Harvesting	June	–	522	Forage harvester	10000	1.0	120	–
	Transport	June	7000	112	Farm trailers	2000	4 × 1.0	20	–
	Ensilaging	June	5050	90	Frontal loader	450	4.0	11.5	–

[a] Cattle slurry composition: 19% dry matter; 1030 kg m^{-3}; 2.85 gN kg^{-1}; 3.6 gP kg^{-1}; 3.75 gK kg^{-1}.
[b] 10% w/v Dicamba, 26.5% w/v MCPA and 29.6% w/v 2,4-D.

Table 3
Field operations timeline and inventory data (per ha) for the cultivation of sorghum and oat (34.27 ha) under a double cropping system.

			Tractor (A)		Operative implement (B)		A + B		
Stage	Activity	Time (month)	Weight (kg)	Power (kW)	Type	Weight (kg)	Effective work capacity (ha h^{-1})	Fuel diesel consumption (L h^{-1})	Input rates
Sorghum cultivation									
Field preparation	Organic fertilisation	June	7000	150	Manure spreader	30000	1.0	18	170 kg N ha^{-1} Cattle slurry[a]
	Ploughing	June	5000	135	Ploughshare	1000	0.5	25	–
	Sowing	June	7000	150	Seeder	700	1.0	20	40 kg seeds ha^{-1}
Crop growth	Weed control	July	4000	75	Spraying machine	500	1.5	10	1.2 L ha^{-1} MCPA
Biomass harvesting	Harvesting	November	–	522	Forage harvester	10000	1.0	120	–
	Transport	November	7000	112	Farm trailers	2000	4 × 1.0	20	–
	Ensilaging	November	5050	90	Frontal loader	450	4.0	11.5	–
Oat cultivation									
Field preparation	Organic fertilisation	February	7000	150	Manure spreader	30000	0.3	18	170 kg N ha^{-1} Cattle slurry[a]
	Ploughing	February	5000	135	Ploughshare	1000	0.5	25	–
	Sowing	February	5000	135	Seeder	600	1.0	20	108 kg seeds ha^{-1}
Biomass harvesting	Harvesting	June	–	522	Forage harvester	10000	1.0	120	–
	Transport	June	7000	112	Farm trailers	2000	4 × 1.0	20	–
	Ensilaging	June	5050	90	Frontal loader	450	4.0	11.5	–

A detailed description of machinery and labour hours per activity for this scenario is presented in Table 3.

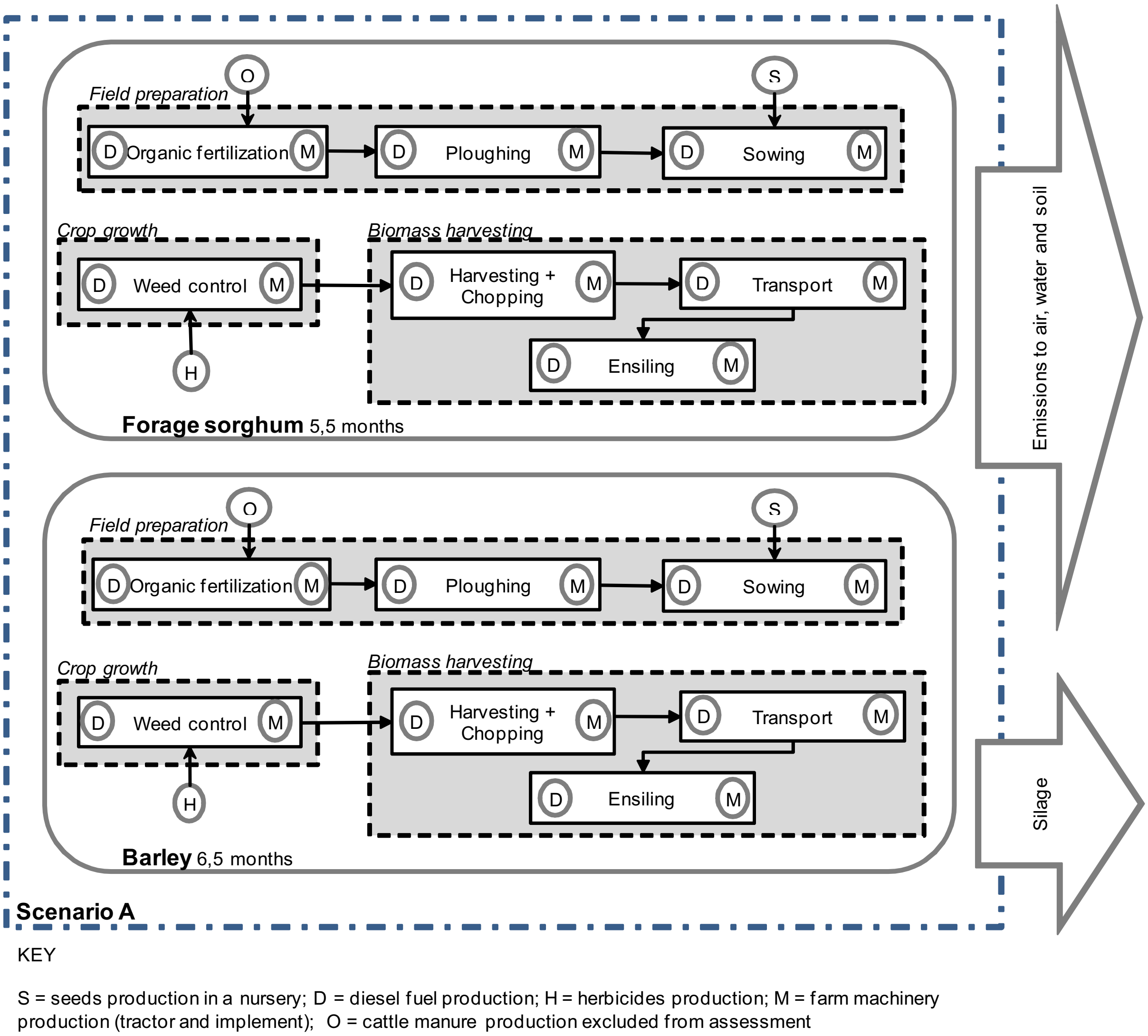
The biomass yields (grain and straw) and moisture content are totally different depending on the crop (see Table 1). Average values of 12.75 t_{DM} ha^{-1} (75% moisture), 7.48 t_{DM} ha^{-1} (83% moisture) and 3.75 t_{DM} ha^{-1} (80% moisture) were assumed for forage sorghum, barley and oat.

2.4. Inventory data acquisition

The Life Cycle Inventory (LCI) for the foreground system (direct agricultural inputs) such as primary and site-specific data (information related to tractors, annual labour hours, diesel and agrochemicals requirements) for both scenarios and for each crop were directly collected on the dairy farm by means of surveys and interviews with growers, taking into account the most advisable agricultural practices and climatic conditions of the region (Tables 2 and 3). The biomass yields of each crop as well as inputs/outputs data regarding consumables were calculated as the average of the biomass yields for the last five years (2009–2014).

Secondary data corresponding to the production of the different inputs was taken from the ecoinvent database® (Ecoinvent, 2015). Although the amount of diesel required for each agricultural operation (fertilising, ploughing, sowing, weed control, harvesting, chopping and ensiling) was supplied by farmers, the production of diesel and the derived combustion emissions were taken from the ecoinvent database® (Nemecek and Käggi, 2007; Spielmann et al., 2007). Inventory data for herbicides production were also taken from the ecoinvent database® (Nemecek and Kägi, 2007). Transport activities related with inputs supply (herbicides, diesel) were obtained from Spielmann et al. (2007). Table 4 reports the name of ecoinvent processes managed and adapted to the characteristics supplied by farmers.

Estimations of toxicity emissions from herbicide application in the different environments require knowledge not only about doses applied, time of application, crops development stage but also local soil characteristics (e.g. pH, composition) and climatic profiles in terms of air temperature, precipitation, solar radiation, number of days with rainfall, average maximum and minimum air temperatures, yearly potential annual evaporation and elevation above sea



(a)

Fig. 1. Scheme of the system boundaries for the double cropping systems under assessment, dedicated to the silage for animal feeding. a) Scenario A—forage sorghum + barley; b) Scenario B—forage sorghum + oat.

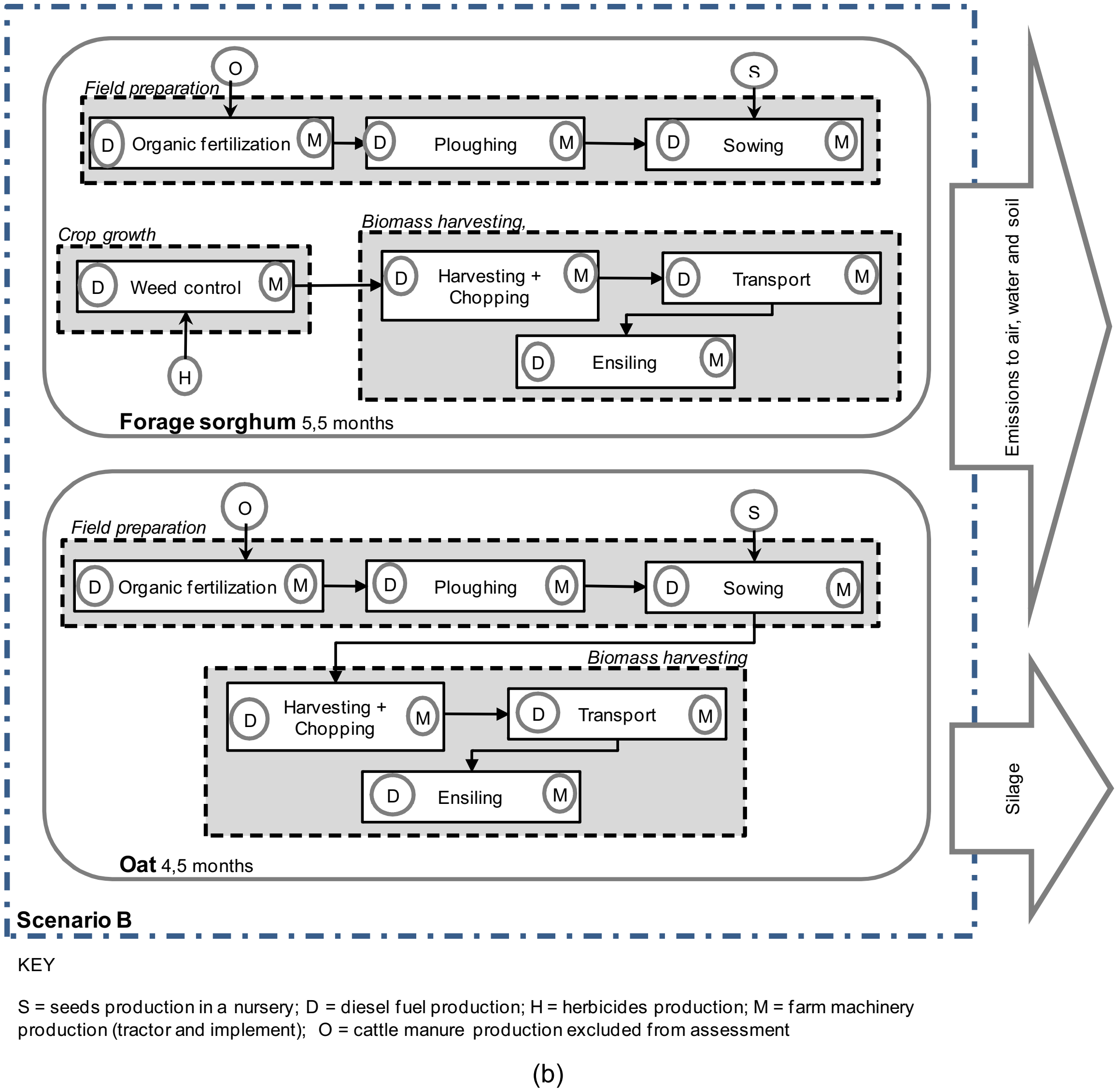


Fig. 1. (*Continued*)

Table 4
Ecoinvent unit processes involved in the background inventory data. Processes in cursive letter correspond to these adapted according to farm characteristics.

Ecoinvent database® process
Slurry spreading, by vacuum tanker/CH
Tillage, ploughing/CH
Sowing/CH
Application of plant protection products, by field sprayer/CH
Combine harvesting/CH
Tractor, production/CH Agricultural machinery, tillage, production/CH
Agricultural machinery, general, production/CH
Barley seed IP, at regional storehouse/CH
Sweet sorghum grains, at farm/CN
Diesel, at regional storage/RER
MCPA, at regional storehouse/RER Dicamba, at regional storehouse/RER
2,4-D, at regional storehouse/RER

level (Dijkman et al., 2012). However, several authors reported that contributions from pesticides or herbicides application could be considered negligible (Goglio et al., 2012). In this study, direct emissions into air from herbicides application were estimated by means of the Dow method (Jansma and Linders, 1995). This model quantifies the volatilisation rates of the herbicides applied from soil. On the contrary, herbicide emissions to other environmental compartments (groundwater and surface water) were not computed in the inventory due to the absence of some of the necessary data for calculation.

Concerning machinery and implements production, similar lifespan and maintenance requirements were considered and inventory data from the ecoinvent database® were obtained on the basis of the operation hours for each agricultural activity (Nemecek and Kägi, 2007).

The fertilising in the crops was totally based on cattle manure as organic fertiliser so no mineral fertilisers were applied. The environmental loads of manure production were allocated to the production of milk and meat in the dairy farm. However, manure handling and field application derived emissions were computed within the system boundaries. According to the farmers, manure is stored in static plastic piles, composted before its use as organic fertiliser. Emission factors used for calculating nitrous oxide (N_2O), ammonia (NH_3),and nitrate leaching (NO_3^-) derived from manure handling and application were taken from Tier 2 and Tier 1 methods, respectively (IPCC, 2006). Methane emissions from manure handling were also calculated following Tier 1 method (IPCC, 2006). Phosphate emissions to water were also calculated for a ratio of

Table 5
On-field derived emissions from cattle slurry handling and management per ha ($57.9\,m^3$).

Output emission	Value
Manure handling	
CH_4 ($kg\,ha^{-1}$)[a]	112
N-N_2O ($kg\,ha^{-1}$)[b]	4.76
N-NO_3^- ($kg\,ha^{-1}$)[b]	98.6
N-NH_3 ($kg\,ha^{-1}$)[b]	81.6
Manure application	
N-N_2O ($kg\,ha^{-1}$)[a]	17.7
N-NO_3^- ($kg\,ha^{-1}$)[a]	51.0
N-NH_3 ($kg\,ha^{-1}$)[a]	34.0
P-PO_4^{-3} ($kg\,ha^{-1}$)[c]	2.15

[a] Tier 1 (IPCC, 2006).
[b] Tier 2 (IPCC, 2006).
[c] Rossier (1998).

0.01 kg PO_4^{-3} kg^{-1} of applied P (Rossier, 1998). Table 5 details the corresponding organic fertilising derived emissions corresponding to the manure rate considered for all the crops: 170 kg N ha^{-1}.

In this agricultural study, no land use changes were considered because the fields under assessment are totally destined to agriculture and no biodiversity losses as well as landscape effects are expected as result of the cultivation of these cereal crops (Milà i Canals et al., 2006; Souza et al., 2015). Regarding water requirements, no irrigation was necessary; therefore, water consumption was excluded from the system boundaries (Milà i Canals et al., 2006). In this cradle-to-gate analysis, all the environmental effects were allocated to the production of silage where the total biomass is simultaneously harvested and chopped.

2.5. Impact assessment methodology

Among the steps defined within the Life Cycle Impact Assessment (LCIA) of the standardised LCA methodology (ISO 14040, 2006), only classification and characterisation were undertaken. Characterisation factors from ReCipe Midpoint methodology were considered (Goedkoop et al., 2008) and the software SimaPro 8 was used for the computational implementation of the inventories.

Agricultural activities involve emissions to the environment and consumption of resources. The environmental effects of these emissions and resources consumption can be illustrated in terms of different impact categories such as acidification, eutrophication, climate change and photochemical oxidant formation, which are considerably affected by CO_2, CH_4, NH_3 and N_2O emissions. In fact, all these impact categories are the most widely used in environmental studies regardless the agricultural system (Buratti and Fantozzi, 2010; Castanheira et al., 2010; González-García et al., 2012; Roer et al., 2012; Bacenetti et al., 2014; Mogensen et al., 2014). Therefore, the following impact potentials were evaluated according to the selected method: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), photochemical oxidant formation (PO), agricultural land occupation (ALO), water depletion (WD) and fossil depletion (FD). Additionally, toxicity related impact categories were also included (González-García et al., 2012; Roer et al., 2012; Bacenetti et al., 2014) such as human toxicity (HT), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET).

3. Impact assessment results and discussion

3.1. Environmental results for the cropping systems under study

The characterisation results are summarised in Table 6 for each impact category and scenario. These environmental profiles (per tonne dry matter) correspond to the average data managed for both scenarios in order to produce cereal silage for cow feeding.

According to these environmental results, the worst environmental results occur in Scenario B, which combines sorghum and oat cultivation except for TET where the impact is 3% lower in Scenario B. The reason behind these results is that Scenario A presents higher biomass yield per hectare: 20.23 t_{DM} vs 16.50 t_{DM} for Scenario B. It is important to remark that these differences on the environmental characterisation results between both double cropping scenarios are also directly related with differences on the silage yield between oat and barley (sorghum yield is identical in both scenarios). Although both crops are winter crops, the biomass yield is much higher for barley than for oat. In the region under study, the average barley silage production per hectare is 7.48 t_{DM} (83% moisture) and for oat, it is considerably lower: 3.75 t_{DM} (80% moisture). The large difference between both yields could be affected by the climatic conditions and/or soil quality since other studies reported similar biomass yields for both crops (Roer et al., 2012). Although there are not so many references concerning the environmental assessment of agricultural practices of oat production (Roer et al., 2012), the biomass yield reported here is considerably lower than the values reported in the literature. On the contrary, barley yield shown in this study is in line with other studies (Roer et al., 2012; Mogensen et al., 2014).

Moreover, although oat cultivation does not require weed control (see Table 3) during the crop growth stage, it is not so remarkable in terms of the environmental profile derived from Scenario B since the contribution from this activity is almost negligible in the sorghum and barley profiles (Scenario A). However, the absence of a herbiciding process (weed control) could affect the oat silage yield since other studies reported different application steps of plant growth regulators, herbicides and insecticides (Roer et al., 2012).

Table 6
Environmental characterisation results for the double cropping systems under assessment per FU (1 t dry matter). Scenario A—Sorghum + Barley; Scenario B—Sorghum + Oat.

Impact categories	Acronym	Scenario A	Scenario B	ScA/ScB
Climate change	CC	232 kg CO_2 eq	282 kg CO_2 eq	82.5%
Ozone depletion	OD	$1.7{\cdot}10^{-5}$ kg CFC-11 eq	$2.0{\cdot}10^{-5}$ kg CFC-11 eq	83.2%
Terrestrial acidification	TA	10.4 kg SO_2 eq	12.7 kg SO_2 eq	81.7%
Freshwater eutrophication	FE	8.4 kg P eq	10.3 kg P eq	81.6%
Marine eutrophication	ME	8.2 kg N eq	10.0 kg N eq	81.9%
Human toxicity	HT	28.1 kg 1,4-DB eq	33.7 kg 1,4-DB eq	83.6%
Photochemical oxidant formation	PO	2.1 kg NMVOC	2.6 kg NMVOC	82.4%
Terrestrial ecotoxicity	TET	0.047 kg 1,4-DB eq	0.046 kg 1,4-DB eq	103.3%
Freshwater ecotoxicity	FET	0.641 kg 1,4-DB eq	0.764 kg 1,4-DB eq	83.9%
Marine ecotoxicity	MET	0.682 kg 1,4-DB eq	0.818 kg 1,4-DB eq	83.4%
Agricultural land occupation	ALO	505 m^2 year	515 m^2 year	98.1%
Water depletion	WD	257 m^3	309 m^3	83.2%
Fossil depletion	FD	46.2 kg oil eq	55.8 kg oil eq	82.9%

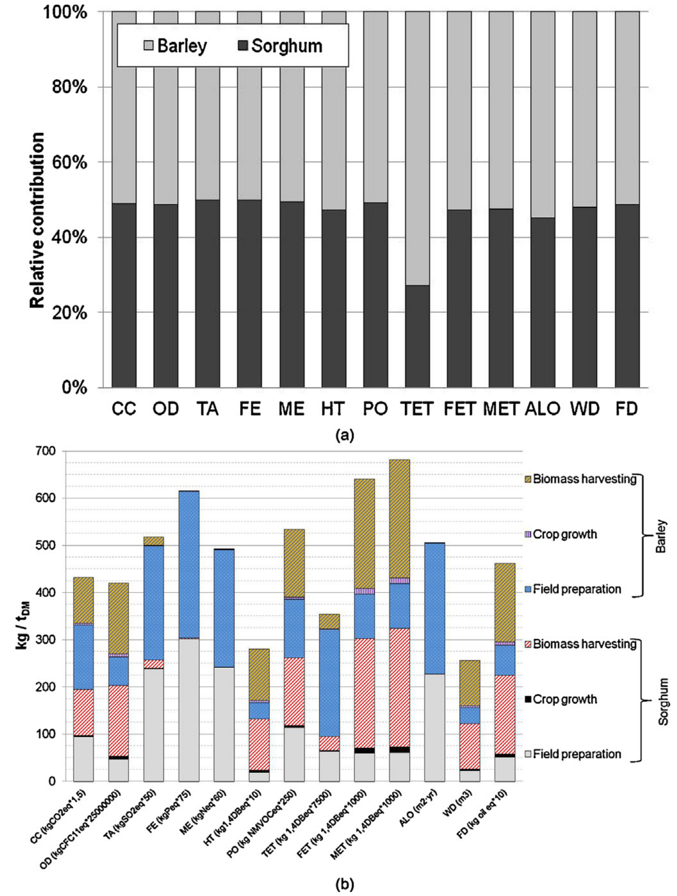


Fig. 2. Environmental profile from Scenario A. a) Distribution of impacts per impact category between the crops involved in the double cropping system. b) Contributions from the different stages to the environmental profile of Scenario A (sorghum + barley). Acronyms: CC = climate change, OD = ozone depletion, TA = terrestrial acidification, FE = freshwater eutrophication, ME = marine eutrophication, HT = human toxicity, PO = photochemical oxidant formation, TET = terrestrial ecotoxicity, FET = freshwater ecotoxicity, MET = marine ecotoxicity, ALO = agricultural land occupation, WD = water depletion and FD = fossil depletion.

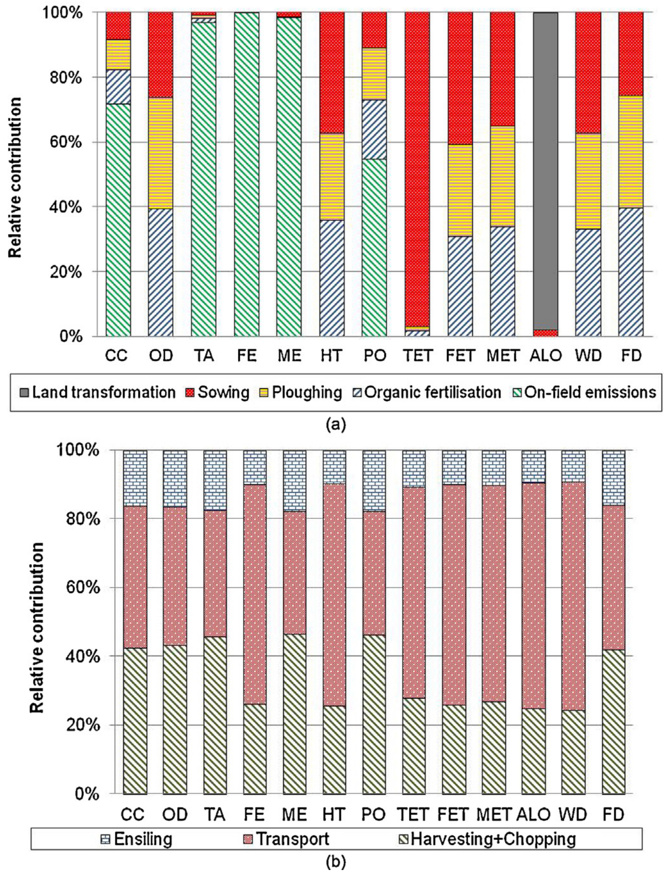


Fig. 3. a) Distribution of environmental loads from activities involved in Field preparation stage (S1) in Scenario A. b) Distribution of environmental loads from activities involved in Biomass harvesting stage (S3) in Scenario A. Acronyms: CC = climate change, OD = ozone depletion, TA = terrestrial acidification, FE = freshwater eutrophication, ME = marine eutrophication, HT = human toxicity, PO = photochemical oxidant formation, TET = terrestrial ecotoxicity, FET = freshwater ecotoxicity, MET = marine ecotoxicity, ALO = agricultural land occupation, WD = water depletion and FD = fossil depletion.

3.2. Scenario A

Fig. 2a shows the global contributions from the activities involved in the cultivation of sorghum and barley to the environmental profile derived from the double cropping system A (Scenario A). According to these results, barley silage production is responsible of more than 50% of impacts in numerous categories (51%–55%) such as CC, OD, ME, HT, PO, TET, FET, MET, ALO, WD and FD. In the remaining categories (TA and FE), the distribution ratios are equivalent for barley and sorghum (50%).

According to Table 2, the same agricultural activities are performed in both crops, using also the same machinery. The main differences are related with the operation hours involved in the organic fertilisation (which also affect diesel requirements), the dose of seeds sown per hectare as well as the type and dose of herbicide applied. These differences are responsible of the differences found for the contribution of sorghum and barley cultivation to Scenario A.

Fig. 2b displays the distribution of environmental burdens for Scenario A per impact category, cropping system and agricultural stage. According to the figure, the environmental burdens mainly derive from two stages: field preparation (S1) and biomass harvesting (S3).

When assessed in more detail, contributions from S1 are the environmental *hotspots* in several categories assessed except in terms of OD, HT, PO, FET, MET, WD and FD where S3 is the critical stage (see Fig. 2b). The large contribution from S1 in CC, TA, FE and ME is mostly related with the on-field emissions derived from the application of manure as organic fertiliser. Both its application and handling involve derived emissions into soil and water such as CH_4, N_2O, NO_x, NH_3, NO_3^- and PO_4^{-3} (see Table 5), which are the main responsible of contributions to CC (40.5% N_2O and 1.6% CH_4), TA (87% NH_3), ME (95% NO_3^-), FE (99% PO_4^{-3}) and PO (25% NO_x). Fig. 3a shows these distributions per processes or activities involved in S1.

Contributions from organic fertilisation and ploughing are directly related with the production of the diesel requirements in the agricultural machinery (manure spreader and ploughshare connected to tractors), combustion emissions associated to diesel use as well as the production and maintenance of the machinery. Both processes are remarkable in categories such as OD, HT, FET, MET, WD and FD. For OD and FD, the contributions come from diesel production and use (around 85% in both categories) and in terms of HT, FET, MET and WD, the impacts (~75%) derive from machinery production (tractors and agricultural implements).

Concerning sowing, this process involves not only seeds application using a seeder connected to a tractor but also the production of sorghum and barley seeds in a nursery. Sowing contributions are important in terms of HT, TET, FET, MET, WD and FD (see Fig. 3a). In contrast to other processes involved in this stage, the production of seeds is the main responsible of derived emissions from sowing in categories such as HT, TET and FET due to agrochemicals requirements. In the remaining categories and in line with ploughing and fertilisation, the production of diesel requirements and tailpipe emissions are the main contributing factors. Concerning ALO, agricultural crop cultivation involves land transformation related activities, which derive on an arable land occupation that explains the contribution to this category (97% of total).

As aforementioned, the stage related with biomass harvesting (S3) reports an important environmental role in some impact categories such as OD, HT, PO, FET, MET, WD and FD. Fig. 3b shows the distribution of the environmental loads derived from this stage to the global environmental profile corresponding to Scenario A. According to the figure, the harvesting process and transport and collection of harvested biomass by tractors within the field are the main responsible activities of these remarkable emissions (82%-91% of total derived emissions from S3). All the environmental loads derived from activities involved in S3 are related with the production of diesel requirements, the corresponding combustion emissions as well as the machinery production and maintenance.

Regarding S2 (crop growth), this stage reports negligible contributions to the global environmental profile derived from Scenario A (see Fig. 2b). Nevertheless, if the contributions derived from this stage were assessed in detail, herbicides production should be a critical factor in terms of FE, ME and toxicity related categories due to emissions derived from their production processes. Emissions derived from the production and use (tailpipe emissions) of diesel required in the spraying machine as well as derived emissions into air from application should be responsible for contributions in the remaining categories.

3.3. Scenario B

Fig. 4a displays global contributions from the activities involved in the cultivation of sorghum and oat to the environmental profile derived from the double cropping system B (Scenario B). The distribution ratios for all the crops to the environmental profile are approximately identical (~50%) in each impact category, except in TET and ALO. Cultivation of oat biomass is responsible of 66% of emissions contributing to TET. Cultivation of sorghum is responsible of 54% of contributions to ALO due to agricultural activities involved in sorghum requires the occupation of the land for 5.5 months meanwhile, 4.5 months are required for oat.

According to Table 3, the same agricultural activities are performed in both crops except weed control, which is not performed in oat cultivation. In line with Scenario B, differences in agricultural practices are related with the operation hours involved in the organic fertilisation and the dose of seeds sown per hectare. These differences are responsible of these minor variations on the contributing profiles from sorghum and oat cultivation to Scenario B.

Fig. 4b shows the distribution of environmental burdens for Scenario B per impact category, cropping system and agricultural stage. In line with Scenario A, the environmental burdens mainly derive from field preparation (S1) and biomass harvesting (S3). In this Scenario B, the contribution from S2 (crop growth stage) to the global environmental profile is almost negligible – less than 2% in all the categories (see Fig. 4b).

On-field emissions derived from manure handling and application are the main responsible of impacts derived from S1 in the following categories: CC (72%), TA (97%), FE (100%), ME (99%) and PO (55%) due to the emission of CH_4 and N_2O (1.6% and 41% respectively of CC), NH_3 (88% TA), NO_3^- (95% ME), PO_4^{-3} (99% FE) and NO_x (25% PO). The remarkable effect from manure derived emissions on the environmental profile associated with S1 is shown in Fig. 5a.

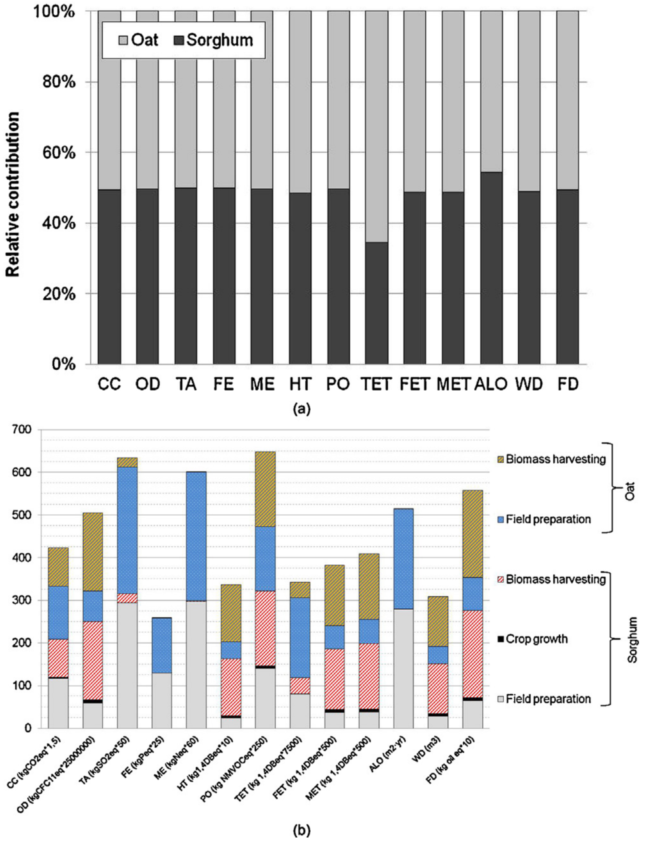


Fig. 4. Environmental profile from Scenario B. a) Distribution of impacts per impact category between the crops involved in the double cropping system. b) Contributions from the different stages to the environmental profile of Scenario B (sorghum + oat). Acronyms: CC = climate change, OD = ozone depletion, TA = terrestrial acidification, FE = freshwater eutrophication, ME = marine eutrophication, HT = human toxicity, PO = photochemical oxidant formation, TET = terrestrial ecotoxicity, FET = freshwater ecotoxicity, MET = marine ecotoxicity, ALO = agricultural land occupation, WD = water depletion and FD = fossil depletion.

The sowing process is important in terms of toxicity related categories (HT, TET, FET and MET) mainly due to the agrochemicals requirements in seeds production. In the remaining categories, the contributions are associated to the diesel requirements in the seeder machinery.

Both organic fertilisation and ploughing processes involve diesel use (and corresponding diesel production) as well as the production of machinery used (manure spreader and ploughshare connected to a tractor). Both processes present total contributions ranging from 65% to 75% (regarding impacts derived from S1) in categories such as OD, HT, FET, MET, WD and FD.

Regarding the biomass harvesting stage (S3), contributions from this stage are important in terms of CC (42%), OD (73%), HT (80%), PO (54%), FET (74%), MET (75%), WD (76%) and FD (73%)—see Fig. 4b. These environmental loads mainly derive from: i) the production and use of diesel in the forage harvester and farm trailers and ii) the production and maintenance of the machinery. As displayed in Fig. 5b, two processes are remarkable *hotspots* in S3: harvesting (including simultaneous chopping) and biomass transport within the farm

3.4. Alternative functional units

A functional unit based on one tonne dry matter (DM) of silage ready to cattle feed production and produced under the best management practices was assumed as base case. According to this unit, Scenario B should be the worse option in order to produce silage for animal feeding mainly due to the lowest biomass yield in comparison with Scenario A.

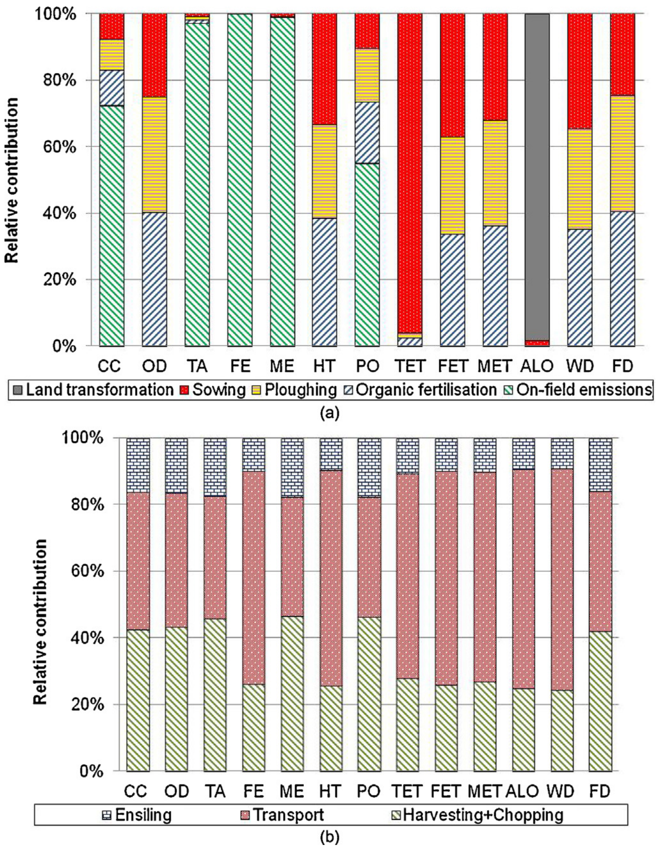


Fig. 5. a) Distribution of environmental loads from activities involved in Field preparation stage (S1) in Scenario B. b) Distribution of environmental loads from activities involved in Biomass harvesting stage (S3) in Scenario B. Acronyms: CC = climate change, OD = ozone depletion, TA = terrestrial acidification, FE = freshwater eutrophication, ME = marine eutrophication, HT = human toxicity, PO = photochemical oxidant formation, TET = terrestrial ecotoxicity, FET = freshwater ecotoxicity, MET = marine ecotoxicity, ALO = agricultural land occupation, WD = water depletion and FD = fossil depletion.

Table 7
Conversion to the alternative functional units considered for assessment.

Scenario	Crop	Yield (t_{DM} ha^{-1})	Crude protein (t ha^{-1})	ME (MJ ha^{-1})
Scenario A	Sorghum	12.75	1.34	151,314
	Barley	7.48	0.94	68,489
		20.23	**2.27**	**219,803**
Scenario B	Sorghum	12.75	1.34	151,314
	Oat	3.75	0.53	31,635
		16.50	**1.87**	**182,949**

A selection of alternative functional units was proposed here since different units could be used in agricultural systems (based on mass production, land occupation, energy content . . .) (Roer et al., 2012). Specifically when crops under assessment are focused on the production of animal feed, the crude protein content and the metabolisable energy content could also be considered as alternative references to report the environmental results. Thus, the alternative functional units proposed for assessment are: a) 1 ha; b) 1 t crude protein and c) 1 MJ metabolisable energy. Table 7 displays the conversions into the different functional units where information shown in Table 1 was managed.

According to the results reported in Fig. 6, the consideration of alternative functional units could considerably change the results and thus, the selection of the best scenario to produce animal feed. These FUs have also been considered in other related studies (Buratti and Fantozzi, 2010; Cerutti et al., 2010; Martínez-Blanco et al., 2009; Fazio and Monti, 2011; González-García et al., 2012; Roer et al., 2012) and play important roles, mostly when crops with different purposes are compared (e.g. food crops and energy crops) (Fazio and Monti, 2011).

The selection of a functional unit based on land occupation could be interesting when there are limitations on the availability of field for agricultural activities. If 1 ha is considered as base for calculation (Fig. 6a), the results considerably change in comparison with the base case (1 t of silage dry matter). Thus, Scenario A (sorghum and barley cultivation) should be the worst option taking into account all the impact categories under analysis, especially in terms of TET and ALO. Although Scenario A presents a high biomass yield, more agricultural activities (e.g. weed control) are carried out, which involves higher diesel requirements, machinery and derived tailpipe emissions per hectare. In addition, Scenario A requires land occupation for 12 months while Scenario B requires 10 months, which has influence on ALO.

If 1 t of crude protein is considered to report the results (Fig. 6b), the profiles follow the trend reported in the base case and Scenario B is again the worst system to produce animal feed. The reductions on the impacts are around 17% for Scenario A in comparison with Scenario B, except in terms of TET, where Scenario B presents a reduction of 4% in comparison with A. The same explanation considered for the base case can be applied here in terms of contributions from the processes involved.

Metabolisable energy (ME) is the net energy available to an animal after the utilisation of some energy in the processes of digestion and absorption and the loss of material as being undigested or indigestible. Concerning the environmental profiles considering 1 MJ of ME as functional unit, Scenario B is also the system with the highest environmental impacts: 16% higher in comparison with Scenario A in all the categories except in TET and ALO (Fig. 6c).

Thus, the environmental profiles when expressed on the basis of mass (tonne dry matter, tonne protein) or energy (metabolisable energy) present similarities. However, it is totally different if the profiles are reported per cultivated area. Thus, the choice of the best system of biomass production for animal feed purposes from an environmental point of view depends on the FU assumed for the calculations.

3.5. *Single crop systems*

Double cropping systems present higher silage production per hectare in comparison with single cropping systems (only one crop is cultivated per area and year) although field operations and agrochemicals requirements are also higher. In this section, crops are separately assessed. The same perspective has been considered in other studies where different feedstuffs (wheat, barley, maize, grass, rape, etc) for dairy cattle have been environmentally evaluated (Roer et al., 2012; Mogensen et al., 2014). As in line with these studies, 1 kg dry matter and 1 ha of occupied area for each crop have been considered as base for calculations (Roer et al., 2012; Mogensen et al., 2014).

Table 8a shows the environmental impacts associated with the cultivation of each crop separately per kg dry matter silage. According to these results, oat silage has higher environmental impact for all the categories considered for evaluation compared to sorghum and barley. Forage sorghum has the lowest impact regardless the category. The impacts derived from sorghum cultivation are around 71% lower compared to oat in all the categories except in terms of TET and ALO, where the impacts are 85% and 65% lower. This reduction on the environmental profile is associated with the highest biomass yield for sorghum in comparison with oat (12.75 t_{DM} vs 3.75 t_{DM}). Although there are other differences on the agricultural practices (diesel requirements in fertilising, ploughing and sowing,

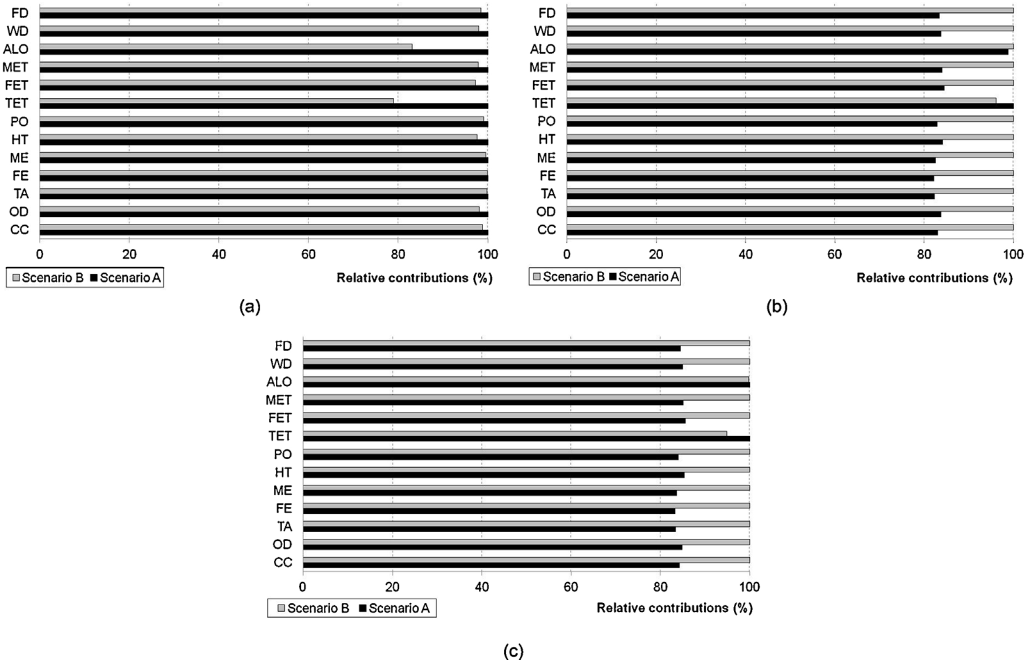


Fig. 6. Comparative environmental profiles between Scenario A and B considering alternative functional units: (a) 1 ha; (b) 1 t of crude protein; (c) 1 MJ metabolisable energy.

Table 8
Environmental impacts from producing sorghum silage, barley silage and oat silage calculated for the functional unit of 1 kg_{DM} silage (a) and for the functional unit of 1 ha (b).

Impact categories/Unit		Sorghum		Barley		Oat	
		(a)	(b)	(a)	(b)	(a)	(b)
CC	kg CO_2 eq	$1.80{\cdot}10^{-1}$	$2.30{\cdot}10^{3}$	$3.21{\cdot}10^{-1}$	$2.40{\cdot}10^{3}$	$6.26{\cdot}10^{-1}$	$2.35{\cdot}10^{3}$
OD	kg CFC-11 eq	$1.30{\cdot}10^{-8}$	$1.65{\cdot}10^{-4}$	$2.33{\cdot}10^{-8}$	$1.75{\cdot}10^{-4}$	$4.48{\cdot}10^{-8}$	$1.68{\cdot}10^{-4}$
TA	kg SO_2 eq	$8.10{\cdot}10^{-3}$	$1.04{\cdot}10^{2}$	$1.41{\cdot}10^{-2}$	$1.05{\cdot}10^{2}$	$2.80{\cdot}10^{-2}$	$1.05{\cdot}10^{2}$
FE	kg P eq	$6.69{\cdot}10^{-3}$	$8.53{\cdot}10^{1}$	$1.14{\cdot}10^{-2}$	$8.54{\cdot}10^{1}$	$2.28{\cdot}10^{-2}$	$8.53{\cdot}10^{1}$
ME	kg N eq	$6.44{\cdot}10^{-3}$	$8.21{\cdot}10^{1}$	$1.12{\cdot}10^{-2}$	$8.41{\cdot}10^{1}$	$2.22{\cdot}10^{-2}$	$8.34{\cdot}10^{1}$
HT	kg 1,4-DB eq	$2.12{\cdot}10^{-2}$	$2.70{\cdot}10^{2}$	$4.01{\cdot}10^{-2}$	$2.00{\cdot}10^{2}$	$7.62{\cdot}10^{-2}$	$2.86{\cdot}10^{2}$
PO	kg NMVOC	$1.67{\cdot}10^{-3}$	$2.12{\cdot}10^{1}$	$2.94{\cdot}10^{-3}$	$2.20{\cdot}10^{1}$	$5.75{\cdot}10^{-3}$	$2.16{\cdot}10^{1}$
TET	kg 1,4-DB eq	$2.04{\cdot}10^{-5}$	$2.59{\cdot}10^{-1}$	$9.31{\cdot}10^{-5}$	$6.96{\cdot}10^{-1}$	$1.32{\cdot}10^{-4}$	$4.95{\cdot}10^{-1}$
FET	kg 1,4-DB eq	$4.81{\cdot}10^{-4}$	6.13	$9.13{\cdot}10^{-4}$	6.83	$1.72{\cdot}10^{-3}$	6.47
MET	kg 1,4-DB eq	$5.15{\cdot}10^{-4}$	6.57	$9.66{\cdot}10^{-4}$	7.23	$1.85{\cdot}10^{-3}$	6.93
ALO	m^2 year	$3.62{\cdot}10^{-1}$	$4.62{\cdot}10^{3}$	$7.49{\cdot}10^{-1}$	$5.60{\cdot}10^{3}$	1.03	$3.88{\cdot}10^{3}$
WD	m^3	$1.96{\cdot}10^{-1}$	$2.50{\cdot}10^{3}$	$3.62{\cdot}10^{-1}$	$2.71{\cdot}10^{3}$	$6.94{\cdot}10^{-1}$	$2.60{\cdot}10^{3}$
FD	kg oil eq	$3.57{\cdot}10^{-2}$	$4.55{\cdot}10^{2}$	$6.41{\cdot}10^{-2}$	$4.80{\cdot}10^{2}$	$1.24{\cdot}10^{-1}$	$4.65{\cdot}10^{2}$

dose of seeds applied and weed control), their contribution is not so relevant on the results.

Regarding barley, the impacts are around 48% lower than oat in all the categories except in TET and ALO, where the reductions are 28%. These minor reductions on the profile are related with the lowest biomass yield for barley in comparison with sorghum, although higher than oat (7.48 t_{DM} vs 3.75 t_{DM} for barley and oat respectively).

Table 8b shows the environmental profile corresponding to the cultivation of each crop separately per occupied area (1 ha). In this case, the selection of a unit based on the area used completely changes the environmental profiles and barley cultivation should be the system with the highest environmental impacts regardless the impact category. Impacts derived from sorghum cultivation are lower compared to barley in ranges from 1% to 63% depending on the category. Once again, the largest reduction ratios correspond to TET and ALO due to the lowest seeds ratio applied for sorghum and land occupation period (5.5 months vs 6.5 months). When it comes to oat, the reduction ratio on the environmental profiles ranges from 1% to 31%. As for sorghum, the highest reduction ratios are in terms of TET and ALO (29% and 31% respectively) due to identical reasons (seeds ratio and land occupation period).

3.6. *Consideration of carbon dioxide fixation*

In Scenarios A and B, the carbon stored by the biomass was not considered within the system boundaries in line with previous studies (Roer et al., 2012; Bacenetti et al., 2014). However, although agricultural activities contribute to climate change with GHG emissions due to the use of diesel in agricultural machinery (mainly CO_2) and manure as organic fertiliser (mostly CH_4 and N_2O), agricultural systems act as CO_2 storage through the photosynthesis process. Thus, CO_2 storage was estimated on the basis of the carbon content in the biomass (dry weight) of the different crops – 46% for forage sorghum, 47.5% for barley and 39.4% for oat (Nemecek and Käggi, 2007; Ort et al., 2016), and multiplying by the stoichiometric factor 44/12.

Fig. 7 shows the global GHG emissions per double cropping system excluding (base case) and including (alternative case) CO_2 storage by the biomass. All GHG emissions produced all over the

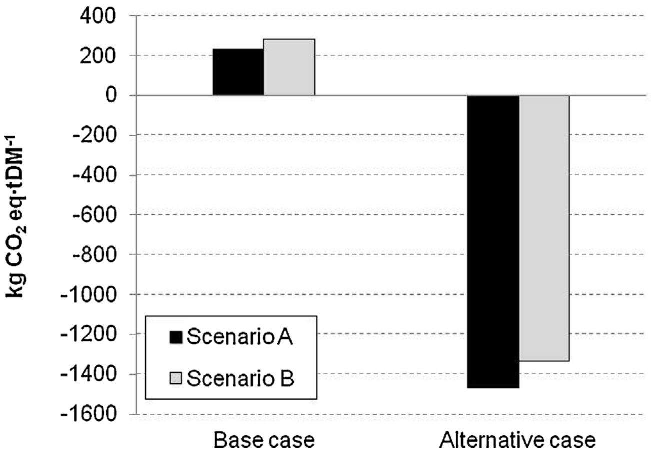


Fig. 7. Equivalent CO_2 emissions per double cropping system excluding CO_2 storage (Base case) and considering CO_2 storage within the system boundaries (Alternative case).

life cycle of the scenarios are offset. CO_2 storage is 10% higher for Scenario A than B due to the higher biomass yield in comparison with Scenario B. Thus and in line with CO_2 balances, Scenario A stores 7.3 times the amount of CO_2 eq emissions produced all over the life cycle of Scenario A (see Fig. 7). Regarding Scenario B, the storage corresponds to 5.7 times the emissions derived from the agricultural activities performed.

3.7. Comparison with existing reports

LCA is a methodology with a certain degree of uncertainty and variability, but it is an useful and comprehensive tool for assessing and characterising the environmental impacts derived from the agricultural systems. Thus, a wide range of agricultural systems focused on cereals production for animal feeding (Flysjö et al., 2008; Roer et al., 2012; Bacenetti et al., 2014; Mogensen et al., 2014; Noya et al., 2015) and food (Niero et al., 2015) have been evaluated in detail.

According to Mogensen et al. (2014), 0.285 kg CO_2eq·$kg_{DM}{}^{-1}$ of barley silage are produced, which is 11% lower than the result reported in our study (Table 7). The rationale behind this difference can be related to different agricultural practices (different fertilisation, seed dose, irrigation and diesel requirements) and different system boundaries (agricultural machinery production and changes on soil carbon content).

Concerning Roer et al. (2012), barley was cultivated under a rotation regime with spring wheat and oat and different yields have been identified in comparison with our study, although it has only been paid attention on grain production (not silage). There are large differences on the agricultural practices performed in both, oat and barley cultivation (doses of fertilisers and herbicides applied as well as agricultural activities and machineries required). However, a similar trend is observed in the contribution of the agricultural processes to the environmental profile. Thus, field emissions derived from fertilising considerably affected CC, FE, ME, TA and PO. Production of diesel requirements contributed to FD and OD while machinery production contributed to toxicity related categories.

Flysjö et al. (2008) studied conventional fodder production in Sweden including barley and oat as crops. However, it was not possible to carry out a direct comparison since system boundaries are completely different, given that production of machinery and buildings, pesticides application and NO_x emissions from fertiliser application were excluded. In addition, in our study grain and straw are joined harvested with a forage harvester and a specific ratio grain/straw is unknown.

Niero et al. (2015) assessed the cultivation of spring barley in Denmark dedicated to grain barley for malting. The production of grain for malting is preferred by farmers versus feed grain since reports higher economic incomes although higher quality is also required (and lower protein content). A functional unit based on grain production (1 kg of DM) was considered to report the results. The study considered all activities carried out as well as capital goods production although differences can be found among countries related to fertilisers (doses and type of fertiliser) and agrochemicals (doses and types) applied and field preparation activities (e.g. harrowing). Grains are dried and straw is incorporated into the soil. Differences were also found in biomass yields – dry matter (5700 kg ha^{-1} in Denmark vs 7480 kg ha^{-1} in our study). Because of these remarkable differences, it is so difficult to compare both studies however, a similar trend is observed in terms of contributing processes. On-field emissions derived from fertilising (mainly these based on nitrogen) and tailpipe emissions from agricultural machinery use dominate the environmental impacts.

Regarding oat, McDevitt and Milà I Canals (2009) carried out a study focused on determining the environmental impacts from porridge oat production in UK where not only the oat cultivation was included but also the further milling. Important differences were identified regarding our study specifically regarding diesel requirements (remarkably higher in our study) and agrochemicals applied. As difference to McDevitt and Milà I Canals (2009), no weed control is performed in our study, which could be associated with differences on soil and climatic conditions. Fuel consumption in the field as well as fertiliser use were again the main responsible of environmental impacts.

4. Conclusions

In this study, the quantification of the environmental impacts derived from two different double cropping systems carried out in Spain in order to produce silage for animal feeding was performed. Considering 1 kg dry matter silage as functional unit, the combination of forage sorghum with barley reported better environmental results than forage sorghum with oat due to the largest biomass yield. Field preparation and biomass harvesting related activities reported the largest contributions to the environmental impacts due to on-field emissions derived from manure application, tailpipe emissions from diesel use in agricultural machinery and seeds production. When considering other functional units, only sorghum and oat based scenario should be preferred when an occupied land based functional unit is managed due to the lowest diesel and herbicides requirements. Thus, functional units based on productivities (crude protein, metabolisable energy and biomass yield) should derive on similar environmental performances.

If the crops are separately assessed (single crops), the production of sorghum silage should be the best option followed by barley silage and oat silage, which is mainly due to the highest silage yield. However, if 1 ha is considered, the barley system should be the worst alternative followed by sorghum and oat mostly due to the highest seed ratio and diesel requirements.

LCA methodology can be considered as a valuable and useful tool to support decision making strategies in agricultural systems. However, this tool presents limitations due to established assumptions accepted by the LCA community. Thus, further research should be focused not only in this study but also in other agricultural environmental studies in order to incorporate specific climate and soil parameters in the analyses which could support additional reliability to the results and considerations.

In addition, attention must be paid to the consideration of emission factors for the calculation of diffuse emissions from manure application. As a general rule, emission factors are taken from literature (IPCC, 2006). However, a global balance of nutrients could be required for a detailed analysis. The use of emission factors omits the nutrients uptakes by crops, which depend on the crops characteristics. Thus, the consideration of emission factors could increase the uncertainty of result

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