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Life cycle assessment of biodiesel in Spain: Comparing the environmental sustainability of Spanish production versus Argentinean imports

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ABSTRACT

The spread of biofuels has generated controversy at international, national and regional levels due to the environmental, economic and social impacts that its production and consumption can cause. Recently, the Spanish government has been promoting the production of biodiesel in industrial plants located in Spain and other EU countries. These developments are expected to stimulate the cultivation of rapeseed in the EU to the detriment of extra-EU imports of biodiesel mainly based on soybean oil from Argentina, which has been one of the main suppliers of biodiesel in Spain for years. As a result, the environmental impacts produced throughout the life cycle of biodiesel consumed in Spain could be radically affected. In this context, the environmental impacts of biodiesel produced in Spain and Argentina with rapeseed cultivated in Spain and soybean cultivated in Argentina were compared under certain growing conditions using life cycle assessment (LCA). Consequential and attributional approaches were compared under the ReCiPe method to test potential biases. The results showed that the biodiesel produced with Argentinean soybean oil had fewer environmental impacts than biodiesel produced with Spanish rapeseed oil. Seed production (and fertilization) was the process (and sub-process) that generated the greatest environmental burdens, and it is an area in which improvement is necessary in order to increase sustainability, particularly with regard to Spanish rapeseed-based biodiesel.

Introduction

Environmental issues have been a key driver for the establishment of policies to promote biofuels in the EU. The European Energy Directive 2009/28/EC (EU-RED) on the promotion of the use of energy from renewable sources (European Commission, 2009), which established a 10% target for energy from renewable sources in transport by 2020, restricts public support only to those biofuels and bio-liquids, produced within or outside the EU, which meet a series of sustainability criteria. In its environmental dimension, it includes requirements for GHG emissions, biodiversity, land use changes and good farming practises. These same criteria were adopted into Spanish law by Royal Decree 1597/2011 (MITYC, 2011). The sustainability criteria set by these regulations mainly affect the agricultural phase in the production of raw materials for use in biofuels. This means that farmers play a crucial role in biofuel sustainability. However, sustainability requirements were not needed in order to comply with biofuel targets in Spain until the 1st January 2016, because of the moratorium on biofuel sustainability established by Royal Decree-Law 4/2013 (Jefatura del Estado, 2013).

In 2011, 45.3% of biodiesel consumed in Spain was produced in Argentina (CNE, 2013), mainly with soybean crops (*Glycine max*), which were cultivated in extensive areas using monoculture techniques but adhering to the 'Round Table on Responsible Soy EU RED' (RTRS) scheme for demonstrating compliance with the sustainability criteria under the EU-RED Directive. By contrast, less than 2% of the total biodiesel consumed in Spain (produced both inside and outside Spain) was produced with rapeseed (*Brassica napus*) (CNE, 2013). In 2012, the Spanish government enacted Order IET/822/2012 (MINETUR, 2012a), and IET/2736/2012 (MINETUR, 2012b) which promotes biodiesel production in European plants. In 2014, the Spanish Ministry of Industry, Energy and Tourism approved an annual production of 4.8 million tonnes of biodiesel for 2014 and 2015 in 37 industrial plants located in the EU, 23 of which are in Spain (MINETUR, 2014). This has undoubtedly affected the biodiesel market, and consequently, the sustainability of biodiesel consumed in Spain. It has resulted in a decrease in imports

Abbreviations: 1,4-DCB, 1,4-dichlorobenzene; ALO, agricultural land occupation; ASME, Argentinean soy methyl ester; CC, climate change; EU-RED, European Energy Directive 2009/28/EC; FD, fossil depletion; FE, freshwater eutrophication; FU, functional unit; GHG, greenhouse gas; HDPE, high-density polyethylene; HT, human toxicity; LCA, life cycle assessment; LCI, life cycle inventory; LDPE, low-density polyethylene; ME, marine eutrophication; OD, ozone depletion; POF, photochemical oxidation formation; RME, rape methyl ester; RTRS, Round Table on Responsible Soy; SME, soy methyl ester; SRME, Spanish rape methyl ester; SSME, Spanish soy methyl ester; TA, terrestrial acidification.

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and an increase in domestic production (Fig. 1). In fact, biodiesel domestic production has already led to a significant expansion of rapeseed (*B. napus*) oil production in Europe in recent years (Malins, 2013). As a consequence, in 2013, the consumption of soy-based biodiesel in Spain decreased by 18.6%, whereas the consumption of rape-based biodiesel increased by 9.7% (CNMC, 2015a).

As a result of new biofuel policies, in future years, a notable increase in first generation biodiesel is expected in Spain (CNMC, 2015b), as well as an increase in rapeseed production (MAGRAMA, 2015a). Therefore, it seems that great uncertainty surrounds the future of sustainable biofuels used in Spain.

As Milazzo et al. (2013) suggest, only demonstrably sustainable feedstock, which complies with sustainability criteria, should be used and promoted by governments in biodiesel production. Therefore, we believe that an in-depth analysis is essential to eliminate uncertainty regarding biodiesel sustainability in Spain so that governments can promote the most sustainable feedstock. Life cycle assessment (LCA) is a widely used technique to analyse the environmental impacts of goods or services. In the scientific community, there is a broad consensus on this being one of the most appropriate methods for assessing environmental impacts associated with the production of biofuels (Requena et al., 2011). LCA allows for the objective comparison of environmental impacts that could potentially be caused by two or more products used for the same purpose. It can be conducted throughout the whole life cycle of a product or service, from production through to consumption, or just for a certain part of the life cycle.

LCA has recently become a key methodology in bioenergy governance, seeking to incorporate externalities that have major implications for long-term sustainability (McManus et al., 2015). It has been used to guide public decision-making toward sustainable production and consumption of biofuels in countries such as Italy (Blengini et al., 2011; Fazio and Monti, 2011) or Malaysia (Yee et al., 2009). The impact of EU biofuel policies on agricultural production, imports and changes in land use has also been examined both at international level (Banse et al., 2011) and in Spain (Lechon et al., 2011). However, most previous LCA studies for rapeseed-based biodiesel do not delve into the specific conditions of production, such as the cultivation techniques or geographical variability (farming locations), which could change the results significantly (Kim and Dale, 2009). This is an additional advantage of the present study, since edaphological and climatic data from the specific locations have been incorporated in the LCI (life cycle inventory) to assess the potential environmental impacts. The same is true for studies of soybean-based biodiesel LCA that have been carried out to date (e.g., Hou et al. (2011) and Panichelli et al. (2009) used mean data in the LCIs for countries such as China and Argentina, respectively). Moreover, most previous studies were limited to energy and greenhouse gas (GHG) emissions, thus excluding other environmental impacts that are relevant throughout the life cycle of the products.

With all this in mind, the objective of this study is to compare the environmental impacts [climate change (CC), ozone depletion (OD), human toxicity (HT), photochemical oxidation formation (POF), fossil depletion (FD), terrestrial acidification (TA), freshwater and marine eutrophication (FE and ME), agricultural land occupation (ALO) and natural land occupation (NLO)] of Argentinean soybean-based biodiesel with biodiesel produced in Spain, both with Argentinean soybean oil and with Spanish rapeseed oil. In the assessment we take into account the specific cultivation techniques, transport of biodiesel or feedstock and geographical variability (Spain or Argentina) of biodiesel production. Only after analysing the environmental burdens of the different systems will it be possible to select the most efficient solutions for improving the sustainability of the biodiesel consumed in Spain. The ultimate aim of this study is to determine whether policies that have been recently enacted to promote biodiesel production in Spain are improving environmental protection, which is the main objective of the promotion of biofuels in the EU, or whether they are in fact having the opposite effect.

Material and methods

Goal and scope

The main objective of the study was to analyse the environmental burdens of biodiesel production systems in Spain in order to contribute to a more efficient design of policies which promote environmentally friendly biodiesel production systems.

The environmental effects of rapeseed-based and soybean-based biodiesel production for the Spanish market were calculated and evaluated using the LCA methodology for three alternative pathways:

A) Argentinean soy methyl ester (ASME): soybean-based biodiesel produced entirely in Argentina and exported to Spain.
B) Spanish soy methyl ester (SSME): soybean-based biodiesel produced in Spain (transesterification) using soybean oil imported from Argentina.
C) Spanish rape methyl ester (SRME): rapeseed-based biodiesel produced entirely in Spain.

The system boundaries included from the raw material extraction up to the factory gate. This study analyses the impacts generated in the cultivation of the raw materials (Argentinean soybean and Spanish rapeseed), grain screening and drying, oil extraction and refining, transportation (of soybean oil or biodiesel from Argentina to Spain) and biodiesel production (methyl transesterification). Therefore, in this study, all the input and output flows of materials and energy up to the factory gate were taken into consideration.

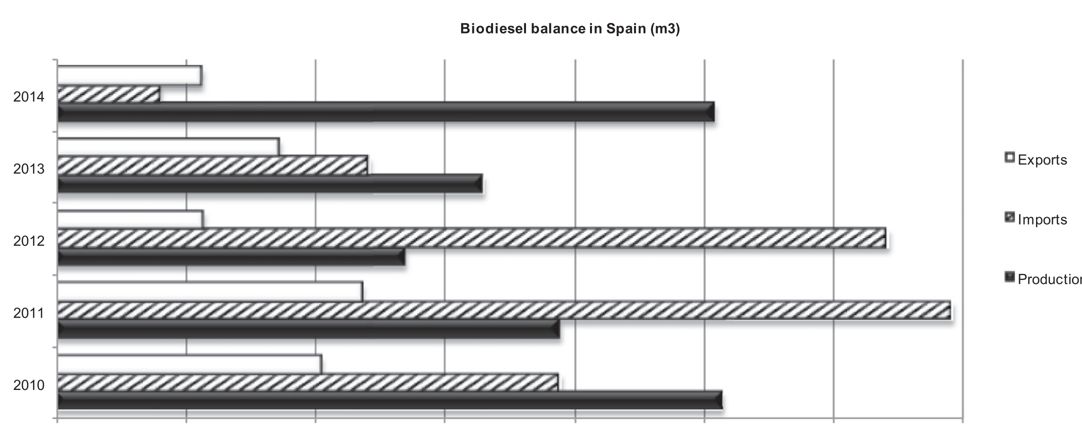

Fig. 1. Biodiesel balance in Spain: exports, imports and domestic production (m^3) Source: CNMC, 2015a.

We used energy content (GJ) as the functional unit (FU), adopting the lower calorific value specified in the EU-RED Directive for biodiesel (37 MJ kg^{-1}).

The software 'Simapro 8.0.4.30' and the database 'Ecoinvent v3.1' (Ecoinvent, 2014) were used for the environmental assessment, taking into consideration the standards set out in ISO 14040 (2006) and ISO 14044 (2006), which specify the general framework, principles and basic requirements for conducting LCA studies.

Life cycle inventory (LCI)

Data for the life cycle inventory (LCI) were collected from different sources. Data sources are specified in Appendix A.

The three production systems considered (ASME, SSME and SRME) were structured in two main phases (agricultural and industrial) for the inventory analysis, each one including processes, sub-processes and flows, in order to facilitate the study and interpretation of the results (Fig. 2). The 'seed production' process (agricultural phase) includes the sub-processes: 'use of farm machinery for agricultural work', 'application of pesticides', 'application of fertilizers' and 'production of seeds for sowing'. 'Land use' (occupation and transformation) was considered as an input from nature. The industrial phase includes: 'grain screening and drying', 'oil extraction', 'oil refining' and 'transesterification'.

Agricultural phase

The outputs from this phase are the seeds needed to produce the oil. The yields obtained in the trials were 2800 kg ha^{-1} of rapeseed in Jerez de la Frontera, Southwest Spain and 3320 kg ha^{-1} of soybean in Pergamino, Argentina. These data were compared with the most recent data available on average national yields. The average yield of Spanish rapeseed in 2013 was 2650 kg ha^{-1}(MAGRAMA, 2015a), while the average yield of Argentinean soybean in 2015 was 3176 kg ha^{-1} (SIIA, 2015). Therefore, our data do not differ greatly from the national averages.

Use of farm machinery for agricultural work

Inputs. A specific process was executed for agricultural machinery in the cultivation of rapeseed in Spain, with a FU of 1 ha (Appendix B). The use of machinery in the soybean crop in Argentina is much more limited because of the no-till farming (NT) system, an agricultural technique in which the soil is not disturbed by tillage. The farm work and agricultural machinery required per hectare in the cultivation of soybean in Argentina were taken from Panichelli et al. (2006) (Appendix B).

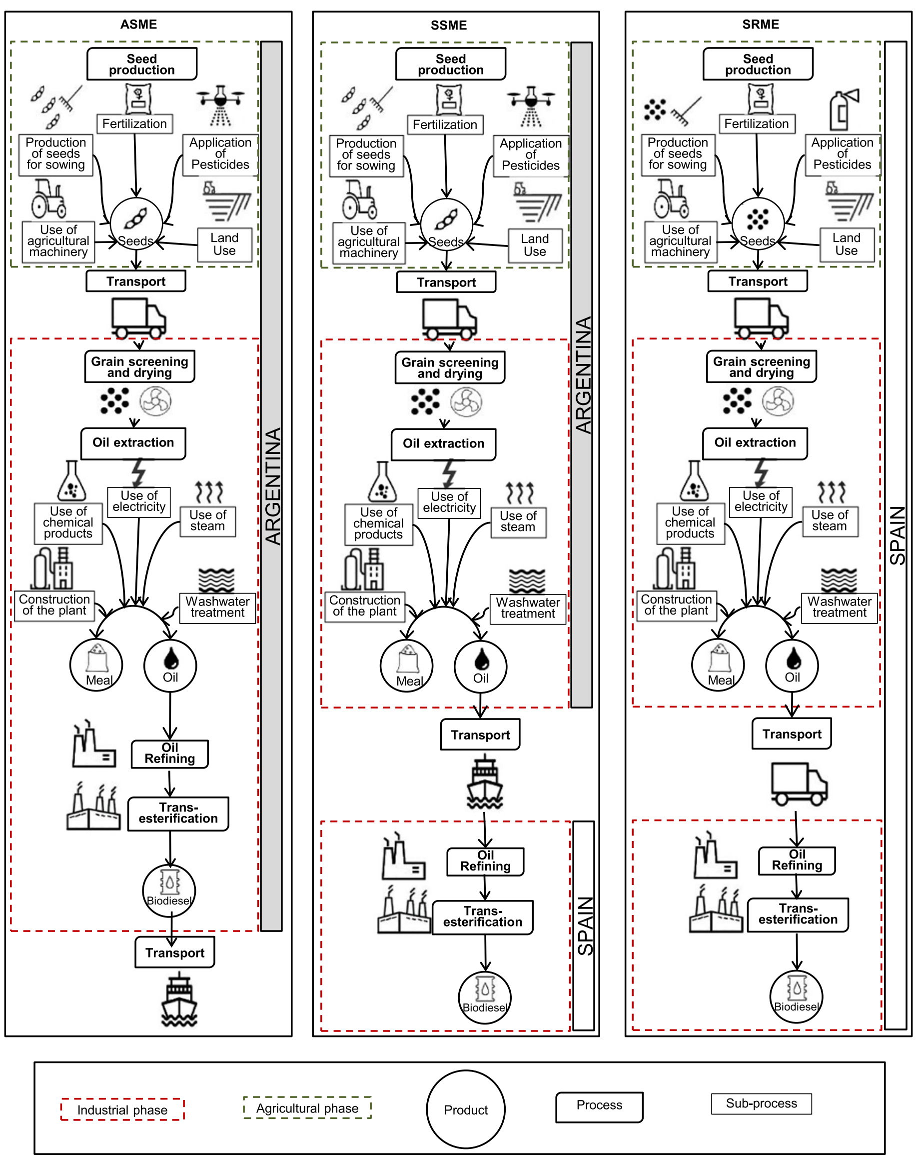

Fig. 2. Flow diagram for the three production systems.

Table 1
Pesticide emission fraction in the analysed case studies (g kg^{-1}).

	Trifluraline emission in rapeseed	Glyphosate emission in soybean
fair	92.5	200.4
fsw	4.7	2.2
fgw	14.6	4.2

fair: fraction of the applied pesticide emitted to the air.
fsw: fraction of the applied pesticide emitted to surface waters.
fgw: fraction of the applied pesticide emitted to groundwater.

Outputs. Air emissions from the combustion of diesel and heavy metal emissions to the soil from the abrasion of the tractor wheels were included in the inventory as outputs in the rapeseed study case (see Appendix B for detailed calculations). These calculations were not needed for the soybean study case, since they were included in the ecoinvent processes that were used.

Application of pesticides. In the rapeseed crop trials carried out in Jerez, 1.5 l ha^{-1} of Trifluraline at a concentration of 48 g l^{-1}, were applied (IFAPA, 2011a). Such treatment is applied simultaneously at the time of sowing. For the cultivation of soybean in the Argentinean Pampa, the most common herbicide used contains glyphosate at a concentration of 48 g l^{-1}. According to the manufacturers of this type of herbicide, in large soybean extensions, two applications of glyphosate, with an average dose of 22.5 l ha^{-1} in each application (mixing glyphosate with water at 10% concentration), are needed once the crop has emerged. The main form of application is spraying from aircraft over large areas of land. The production of pesticides and their transport to the application site were incorporated as inputs for both crops in the inventory of pesticides. The procedure for calculating these inputs is summarized in Appendix C.

With regard to emissions from pesticide application, in recent years, complex mathematical models called 'fate analyses' have begun to be used frequently in LCAs of agricultural systems to evaluate the transport of agrochemicals by environmental compartment. Fate analysis models give more precise information than emission factors. In this research, the PestLCI model developed by Birkved and Hauschild (2006) was used to calculate pesticide emissions. This model quantifies the fraction emitted to the atmosphere, surface water and groundwater from the following equation:

$$fem = mem/mappl = fair + fsw + fgw \quad (1)$$

where *fem* is the fraction of pesticide that is emitted into the surrounding environment, *mem* is the mass of pesticide emitted to the environment, *mappl* is the mass of pesticide applied, *fair* is the fraction of the applied pesticide which is emitted to the air, *fsw* is the fraction of pesticide released to surface waters and *fgw* is the fraction emitted to groundwater. Each of these fractions is calculated through a complex series of equations which are fully described by Birkved and Hauschild (2006).

The PestLCI model was implemented on an Excel spreadsheet which includes a database with the physical and chemical properties of 69 pesticides and different types of application (incorporation into the soil, spray, etc.). The model parameters are related to crop type and stage of development, as well as agronomic and climatic variables. The PestLCI database gives soil and climate data for Danish conditions. It was therefore necessary to collect data under the specific conditions of the analysed case studies to be incorporated into the model. Climate and soil data were taken from IFAPA (2011b) and Monge et al. (2008) for the rapeseed crop in Jerez and from INTA (2013) and INTA (2002) for the soybean crop in Pergamino. Table 1 shows the emission of active substances in the pesticides into the different areas of the environment, which were calculated with PestLCI and inserted into SimaPro.

Table 2
Mass fraction of nutrients contained in the fertilizers and mass of fertilizer applied (kg/ha).

	Nutrient content of the fertilizer (%)				Mass of fertilizer applied (Kg/ha)	
Fertilizer type	N	P_2O_5	K_2O	S	Soy	Rape
Urea	46	–	–	–	72.7	149.3
Triple superphosphate	–	48	–	1	44.9	86.5
Potassium sulphate	–	–	52	18	34.5	81.8
Potassium nitrate	14	–	44	–	19.5	4.5

Table 3
Emissions from mineral fertilizer application (mass fraction of emitted substance per nutrient applied).

Substance	Compartment	Emission factor	Source
NH_3 (%)	Air	4% N	Audsley et al. (2003)
N_2O (%)	Air	1% N	De Klein et al. (2006)
NOx (%)	Air	21% N_2O	Nemecek and Kägi (2007)
P (kg/ha*a)	Groundwater	0.07	Nemecek and Kägi (2007)
P (kg/ha*a)	Surface water	$0.175*(1 + 0.0025[P_2O_5])$	Nemecek and Kägi (2007)
SO_4 (%)	Groundwater	72% S	Riley et al. (2002)

Application of fertilizers. In both case studies, a rational fertilization of the crops was analysed. Rational fertilization is understood to mean the fertilization required in order to return to the soil the nutrients taken out by previous crops (García-Serrano Jiménez et al., 2010). The LCA of the fertilization of the two case studies analysed was studied by Fernández-Tirado et al. (2013). The inputs and outputs were taken from the LCI of that study. In both case studies, it is assumed that the stubble is left on the field, since this is a common practise for the systems analysed in both study areas. Thereby, the stubble contributes to the replacement of nutrients in the soil, after the processes of humification and mineralization. In order to carry out a rational fertilization, firstly, the annual loss of nutrients, mainly due to the removal of nutrients by the grain was calculated. Secondly, the annual rates of nutrient replacement from the stubble to the soil were estimated. Finally, the nutrient requirements to maintain the amount of nutrients constant were calculated, in order to balance these with mineral fertilizer. Table 2 shows the four common commercial fertilizers used in this study, their typical nutrient composition and the mass of fertilizer applied.

Regarding the emissions, Table 3 shows the emissions factors which were selected for the LCI of this research for the application of mineral fertilizers and their literature sources.

Moreover, the packaging of fertilizers in 50 kg LDPE bags has been taken into account. A weight of 23 g for every bag was taken into consideration, as was its recycling.

Production of seeds for sowing. The seed is produced and processed prior to planting. In such processes, three inputs were taken into consideration. Firstly, the above-mentioned production process of seed cultivation itself was included in our calculations. While 7 kg of seeds are needed to grow one hectare of rapeseed (IFAPA, 2011a), 75 kg are needed to grow one hectare of soybean (Panichelli et al., 2006). Secondly, the transport needed to bring the seeds from the field to the processing

Table 4
Impact categories and indicator units at midpoint.

	Impact category	Indicator unit
Climate change	CC	kg (CO_2 to air)
Ozone depletion	OD	kg (CFC-11 to air)
Terrestrial acidification	TA	kg (SO_2 to air)
Freshwater eutrophication	FE	kg (P to freshwater)
Marine eutrophication	ME	kg (N to freshwater)
Human toxicity	HT	kg (14DCB to urban air)
Photochemical oxidant formation	POF	kg (NMVOC to urban air)
Agricultural land occupation	ALO	m^2 yr (agricultural land)
Fossil depletion	FD	kg (oil)

Source: Goedkoop et al., 2013.

Table 5
Mass, economic and energy allocation factors used in the attributional approach.

	Production (tonnes)	Price (USD/t)	Lower calorific[a] value (MJ/kg)	Allocation		
				Mass	Economic	Energy
Rape oil	1025	781	37.8	39%	74%	67%
Rape meal[b]	1574	270	18.7	61%	26%	33%
Total	2599	1051	56.5	100%	100%	100%
Soy oil	1025	778	36.6	19%	65%	69%
Soy meal[c]	4333	423	16.3	81%	35%	31%
Total	5358	1201	52.9	100%	100%	100%

[a] Lower calorific values for rape meal and soy oil: BIOGRACE (2015); for soy meal Castanheira et al. (2015); and for rape oil Grau et al. (2013).
[b] 34%, Hamburg, f.o.b. ex-mill (FAO, 2015).
[c] 45/46% Argentinean c.i.f. Rotterdam (YCHARTS, 2015)

plant and, once processed, to bring them back to the field was also included. The selected truck is considerably heavier for the soybean crop (over 32 t) than for the rapeseed crop (7.5–16 t) (Gasol et al., 2007), not only because soybean farmers require more seeds per hectare, as indicated above, but also due to the economies of scale which generally exist in the soybean plantations of Argentina. We took a standard distance of 15 km between the field and the plant, in accordance with the standard distance used by Nemecek and Kägi (2007) and Jungbluth et al. (2007). Finally, the energy used to process the seed is calculated in the same way as in Gasol et al. (2007), i.e. 58 kWh per tonne of seed.

Land use

Land occupation. The term 'land occupation' refers here to the agricultural area required to produce the grain needed to produce the amount of biodiesel equivalent to the same functional unit (1 GJ) and duration (1 year). The industrial area is not significant in comparison with the agricultural area and was not taken into account. Whereas 261 m^2 are needed to produce 1 GJ of SRME, 467 m^2 are needed to produce 1 GJ of ASME and SSME. These values are so different because soybean has a very low oil content, meaning that large areas of land are required to obtain the same amount of biodiesel.

Land transformation. Soils represent a large sink of organic carbon and land transformation can induce GHG emissions due to changes in carbon stocks. Land transformation can occur for various different reasons, such as crop change, crop intensification or land use change (LUC). Moreover, LUC is divided into direct land use change (dLUC), meaning the change of use of the piece of land occupied by the crop, and indirect land use change (iLUC), meaning the change of use of areas other than cropland itself.

In this study, it is assumed that agricultural production increases by area expansion and not by intensification. However, dLUC has not been considered, since the crop is expected to occupy an existing cropland, so the use is still agricultural production. Therefore, in terms of dLUC, there is no land use change but there is crop change, i.e. there is no transformation to arable land but rather occupation of non-irrigated arable land by the energy crops. Due to the 'greening' requirements of the EU's Common Agricultural Policy, crop diversification is expected to increase in Europe for farmers to qualify for agricultural subsidies. In Andalusia, the 'RAEA-Biofuels' project conducted by IFAPA recently confirmed in tests that rapeseed produces high yields (IFAPA, 2011a) and it is expected to continue spreading (MAGRAMA, 2015a). A change of crop is anticipated from wheat, the grain that occupies the greatest area in Andalusia, to rapeseed, in wheat–rape rotations, due to the high yields that this rotation produces (García de Tejada, 2015) and this was assumed in the SRME scenario. In Argentina, the area sown with soybean has increased noticeably since the end of the 1990s, mainly in the Pampa region, because of its bioclimatic suitability for this crop. In the season of 1996–1997, the soybean area was similar to the wheat area, whereas in 2012, the soybean area was four times the wheat area (OSAS, 2015). Hence, the same assumption (conversion from wheat) was made for the ASME and SSME scenarios. Moreover, the iLUC effect was taken into account through displacing the areas cultivated with wheat in Argentina or Spain to other areas, assuming transformation to arable land.

Furthermore, carbon loss from iLUC was estimated at 2.85 tm C/ha/year over a 20-year time horizon, i.e. it was assumed that the land would be used for over 20 years for biofuel production. In order to calculate this, first a conversion factor of 57 t C/ha was taken from IEEP (2011), based on an average of the IPCC default data (IPCC, 2006). Then, it was annualized over a 20-year time horizon.

Transport

Once harvested, the seeds must be transported to the plant. In Argentina, 85% of the harvest is moved by lorries, which carry about 30 t. Therefore, the chosen vehicle to bring seeds to the plant (ASME and SSME scenarios) is a lorry weighing 16 to 32 t. The technology of the type of lorry chosen was the one which complies with the Euro III standard, as it is the most abundant type of lorry in the Argentinean fleet. The same type of vehicle was chosen to transport the rapeseed harvested in Spain (SRME scenario), since the Euro III technology is also the most abundant in Spain (Fernández-Tirado et al., 2013). Finally, the transport processes carried out in every scenario were described.

In the ASME pathway, the seeds are transported by road a distance of 134 km, which is the current average distance between the growing area (Department of Pergamino in the province of Buenos Aires) and the towns of Puerto General San Martin, San Lorenzo and Rosario, where most of the oil and biodiesel industries are located (CARBIO, 2012). Argentina's biodiesel industries are located very close to the ports. An average distance of 10,181 km was calculated from the port of Rosario (Argentina) to Algeciras and Palos de la Frontera (Spain), where the main refineries and biodiesel industries of western Andalusia are located. The shipping of biodiesel was taken into account for the ASME scenario and soybean oil shipping for the SSME scenario.

In the SRME scenario, the oil is not extracted in the biodiesel plant, but in other nearby industries. Seeds are transported 70 km by road in lorries weighing 16 to 32 t. This is the distance between the growing

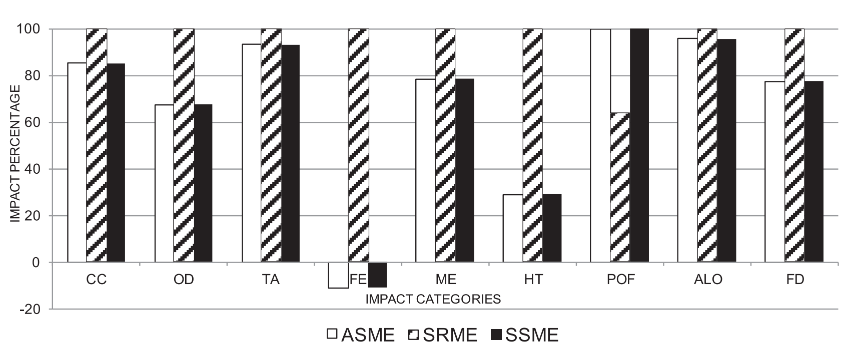

Fig. 3. Environmental impacts of ASME (Argentinean soy methyl ester), SRME (Spanish rape methyl ester) and SSME (Spanish soy methyl ester) according to the ReCiPe Midpoint (H) method and the consequential approach.

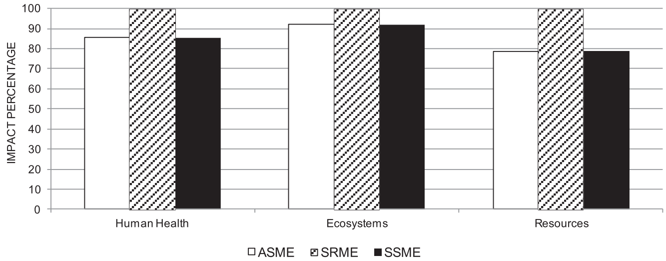

Fig. 4. Environmental impacts of ASME (Argentinean soy methyl ester), SRME (Spanish rape methyl ester) and SSME (Spanish soy methyl ester) according to the ReCiPe Endpoint (H) method and the consequential approach.

area (IFAPA Rancho de la Merced) and the nearest oil extraction industry that can use rapeseed in Western Andalusia, which is located in Osuna (Seville). Andalusia has about 40 industrial plants for extracting oil from oilseeds, mainly sunflower. Then, the oil has to be transported to the biodiesel industries, which are at an average distance of 99 km from the oil extraction industry and the two biggest biodiesel industries in Andalusia.

Industrial phase

The energy and mass of raw material used in every process varies depending on the characteristics of each industry, such as technology or the size of the industrial plant. Both Andalusian industrial plants, Abengoa Bioenergía San Roque, S.A. and Bio-oils Huelva, S.L.U. are large-scale and use Desmet-Ballestra technology. Most of the Argentinean biodiesel industries use the same technology as European plants (Lurgi, Westfalia, Desmet Ballestra or Crown Iron Work) and are large scale. Thus, the same industrial processes were taken into consideration for all scenarios, regardless of whether production takes place in Spain or Argentina. The industrial phase includes: grain screening and drying, oil extraction, oil refining and transesterification. Appendix D shows a literature review of mass and energy use in the industrial processes per tonne of methyl ester produced, as well as the data used in this study.

Grain screening and drying. First, the plant feedstock must be cleaned so that any foreign matter is removed. This applies particularly to sand/silicate and iron, which may damage the preparation plant equipment. In the screening process, particles with a density higher than 150 mg/nm^3 are filtered out (CIEMAT, 2006). About 2% of the weight of the material is filtered (Esteban et al., 2011). Next, the seeds are dried by passing a stream of air through them. According to Hamm et al. (2013), rapeseed must be dried until the moisture content is 5%, while it is harvested with a moisture content of 9% according to recommendations from (IFAPA, 2011a). Soy is harvested with a moisture content of 16% according to recommendations from Behr et al. (2011) and has to be dried until the moisture content is 11% (Hamm et al., 2013). Heat can be generated from natural gas or diesel (HGCA, 2011). The use of natural gas is more common in both Argentina and Spain. According to Donato and Huerga (2009), the energy consumption in the drying process can be calculated using Eq. (2).

$$E = [Hi\text{–}Hf] * \eta \tag{2}$$

where E is the energy needed in the drying process (Kcal/kg seed); Hi is the initial seed moisture content (kg water/kg seed), Hf is the final seed moisture content (kg water/kg seed) and η the drying efficiency of the dryer (Kcal/kg water). A conventional dryer has a drying efficiency of 1020 kcal per kg of evaporated water (De Dios, 1996).

Oil extraction. Rapeseed can have more than twice the oil content of soybean. In this process, in the case of rapeseed, 2.52 kg of seed are needed to produce 1 kg of oil and 1.25 kg of meal, while in the case of soybean, 5.60 kg of seed are needed to produce 1 kg of oil and 4.36 kg of meal. First, the seeds are crushed to reduce the particle size and then flaked. The hulls are removed by aspiration and blended with the meal that is later extracted in the process. The oil is extracted mechanically (pressing and rolling) from the kernel. In addition to the extracted oil, a cake with high oil content is produced. The oil is extracted from the cake by chemical means (solvents). Hexane is the most commonly used solvent and is mostly recycled for reuse in the extraction process. Modern solvent extraction plants recover over 99.9% of the solvent pumped into the extractor (Hammond et al., 2005; Hamm et al., 2013). In keeping with EPA (1995) and Gabi (2011), we included values of 2.16 kg and 1 kg of hexane loss per tonne of soybeans and rapeseed respectively in our calculations.

Oil refining. The oil refining process is carried out in the biodiesel plant after receiving the crude oil. This process includes

Degumming: the crude oil is mixed with phosphoric acid, at a concentration of 0.1%–0.3% by weight of oil, and hot water (75 °C–90 °C) to remove gums (by-product).

Caustic treatment: the excess of phosphoric acid is removed by reaction with a solution of NaOH. The quantity of caustic substance, known as the treat, can be calculated as in Eq. (3) (Kitani et al., 1999):

$$Treat = [(0.142\ FFA) + excess]/(\%NaOH/100) \tag{3}$$

where FFA is the percentage of free fatty acids, which is 1.05% in degummed soybean oil (Fornasero et al., 2013) and 0.55% in degummed canola oil (Ghazani, 2012), excess is the excess of caustic, and % NaOH is the caustic concentration. Suggested caustic concentrations and excess were taken from O'Brien (2004).

Filtration: bentonite clay (natural absorbent) and TriSyl (synthetic absorbents) are used to filter the degummed oil.

Deacidification: the free acids contained in the oil are removed 'physically' by volatilization at a pressure of 1 mbar and a temperature of 240 °C–260 °C. The free acids removed are used later in the esterification process.

Table 6
Values of the impact categories for the three pathways of biodiesel production: ASME (Argentinean soy methyl ester), SRME (Spanish rape methyl ester) and SSME (Spanish soy methyl ester) according to the ReCiPe Midpoint (H). Functional unit: 1 GJ.

		No allocation			System expansion		
Impact category	Indicator unit	ASME	SRME	SSME	ASME	SRME	SSME
CC	kg CO_2 eq	602	329	602	240	281	240
OD	kg CFC-11 eq	1.05E-05	6.95E-06	1.05E-05	4.22E-06	6.28E-06	4.24E-06
TA	kg SO_2 eq	1.98	1.06	1.99	0.842	0.90	0.844
FE	kg P eq	0.0116	0.0124	0.0116	−0.00128	0.0115	−0.00127
ME	kg N eq	0.116	0.0677	0.116	0.0465	0.0591	0.0465
HT	kg 1,4-dB eq	17.4	14.0	17.4	3.72	12.9	3.73
POF	kg NMVOC	0.990	0.422	0.992	0.545	0.349	0.547
ALO	m^2 yr	492	255	492	206	215	206
FD	kg oil eq	23.3	15.2	23.4	10.7	13.8	10.7

Transesterification and purification. The refined oil reacts with excess methanol in the presence of a catalyst. Sodium methoxide is used as the catalyst, at a concentration of 0.4% of the weight of the oil (Babu et al., 2013). Four reactors are used in the transesterification process, in which methyl ester (or biodiesel) and glycerol are obtained as the main products. In order to separate the two products, the glycerol is decanted. The biodiesel is washed to remove the rest of the methanol, glycerol, catalyst and soaps. A conventional wet purification process is carried out (acid water washing). Citric acid is used in this process as a washing agent, at a concentration of 0.1 M (Serrano et al., 2013) or 19.2 g/L.

In accordance with Berrios and Skelton (2008) and Lamers (2010), a water/biodiesel ratio of 0.5/1 was used in our calculations, employing multiple successive washing steps. Most of the new biodiesel industries have a wastewater treatment plant and most of the industrial process water which is not evaporated is reused. In the evaporation processes, the excess of water in the products is removed. The water content of the biofuel after the washing steps is around 0.5%. This value is above the maximum set by the standards (0.03%) and it is therefore necessary to dry it. Crude glycerol of about 85 wt% also has to be purified to obtain a product with a purity of at least 99 wt%. Water elimination is necessary when average moisture content is in the range of 4% to 0.95% (Ayoub and Abdullah, 2012). Therefore, 4.7 kg of water are evaporated from biodiesel and 4.1 kg of water from glycerol per tonne of biodiesel produced in the drying process. Moreover, 12 kg of tap water is used by the staff per tonne of biodiesel produced (80 kg per person per eight-hour shift). The excess methanol is also removed in the evaporation process and is recycled in the transesterification process. Most of the catalyst is also recovered but a small part is consumed producing soaps and sodium citrate. The glycerol is purified by using hydrochloric acid to remove free acids. Then, the acid glycerol is neutralized with sodium hydroxide. The free acids coming from the glycerol purification and oil refining are also used to produce biodiesel in the acid esterification process using sulphuric acid as a catalyst and methanol.

Life cycle impact assessment (LCIA)

The ReCiPe methodology with a hierarchic perspective was used to quantify the impacts in the LCIA phase (Goedkoop et al., 2013). ReCiPe uses two strategies, midpoint (problem oriented) and endpoint (damage oriented), and comprises two sets of impact categories with associated sets of characterization factors. The midpoint characterization factors are multiplied by the damage factors to obtain the endpoint characterization values (Pré, 2015). Both strategies, midpoint and endpoint, were used in this study. Table 4 shows the indicator units for every selected impact category at midpoint.

In the endpoint assessment, damages to human health, ecosystems and resources are assessed.

Allocation procedures

Allocation refers to the distribution of environmental burdens between co-products of a multifunctional system. The main co-products in the systems studied are biodiesel and glycerol from the transesterification process, and press cake (or meal) and oil from oil extraction. However, current biodiesel production has flooded the market with glycerol, leading to a drop in market prices (Esteban et al., 2011). Therefore, no allocation was made to glycerol and the environmental burdens were shared between oil and cake in the oil extraction and refining process.

According to ISO 14040, allocation should be avoided wherever possible by (1) dividing the unit process to be allocated into two or more sub-processes and (2) expanding the product system to include the additional functions related to the co-products. In our case studies, system expansion is possible and, as ISO 14040 recommends, this was chosen as the first option, instead of allocation methods (energy content, economic value, mass, etc.) which are usually collectively referred to as the attributional approach. In system expansion, also known as the consequential approach or substitution method, the inputs and outputs are entirely ascribed to the process (biodiesel production), while the system is expanded to include the products that can be avoided due to the production of co-products (press cake). That way, the environmental impacts of co-products are subtracted. It was assumed that soy meal can be substituted by rape meal and vice versa. As they are coproduced with oil, this introduces another need for system expansion, leading to a never-ending cycle which has been described as the soybean–rapeseed loop (Dalgaard et al., 2007). Therefore, at some point, it is necessary to use an allocation method to estimate the environmental load of the co-product. The meals coproduced are used almost exclusively for animal feed. However, neither mass nor energy allocation are good approaches for biofuel systems because they do not recognize the nutritional differences between the oilseed meals. Instead, we used the economic allocation procedure as suggested by Reinhard and Zah (2011) and in keeping with the ecoinvent database for bioenergy products (Jungbluth et al., 2007), where the allocation of environmental impacts between co-products is based on the respective prices of the co-products. Average international prices were taken for the period Oct. 2014–Sep. 2015 and are shown in Table 5. Therefore, the use of local rapeseed meal to feed animals displaces the soybean meal in the ASME and SSME scenarios in order to discount its credits. Similarly, the use of imported soybean meal to feed animals displaces the rapeseed meal in the SRME scenario. As a result, 1 kg of rape meal is equivalent to 0.64 kg of soybean meal.

Sensitivity analysis

The sensitivity analysis is an optional element of LCA to estimate the validity of the results of the LCIA. In this study, it was performed as recommended by ISO standards. The environmental load was shared between co-products according to the attributional approach through allocation based on energy content, mass and price. Table 5 shows the allocation factors taken into consideration in the assessment.

Moreover, a scenario without allocation was contemplated, where all emissions and energy used solely burdened the biodiesel.

Results

All results are plotted on a percentage scale. The figures show a comparison between the impacts caused by the different pathways of biodiesel production. The vertical axis is a percentage scale of every impact category. The highest score, i.e. the pathway which causes the highest burden, is scaled to 100% and the others are relative scores.

The results obtained show that when the consequential approach (avoided burden) is used (Fig. 3), the Spanish rapeseed-based biodiesel pathway (SRME) causes higher environmental impacts than the soybean-based biodiesel in both pathways (ASME and SSME) in all the selected midpoint impact categories, except in POF, where the SRME pathway causes 64% of the impacts caused by the ASME and SSME pathways. The burdens of soybean-based biodiesel production (ASME and SSME pathways) represent 29% to 96% of the burdens caused by Spanish rapeseed-based biodiesel production (SRME) in the categories HT (29%), OD (67%), FD (78%), ME (79%), CC (85%) TA (93%) and ALO (96%). Moreover, soybean-based biodiesel produces positive impacts (shown as negative in Fig. 3) in the FE category, due to credits of rape cake which are discounted in the system expansion procedure.

The damage analysis carried out using the ReCiPe Endpoint (H) and system expansion (Fig. 4) shows that SRME causes the highest impacts in the three damage categories (human health, ecosystems and resources).

Table 6 shows the values returned for the impact categories when system expansion is carried out, as well as when any allocation is used (i.e. allocating 0% of burdens to press cake). The differences between them are due to the credit discounted for the press cake in the consequential approach.

The effects of every process in the impact categories were analysed, so that decision makers can focus on those processes which cause higher environmental impacts. As Fig. 5 shows, 'seed production' is the process with the greatest effect in most of the selected impact categories for all the pathways (ASME, SRME and SSME). 'Oil extraction and refining' is the second most critical process. However, Fig. 5 shows negative values, i.e. positive impacts in most of the categories addressed for the 'oil extraction and refining' process. The negative values are due to the fact that this process is highly influenced by the credits which are

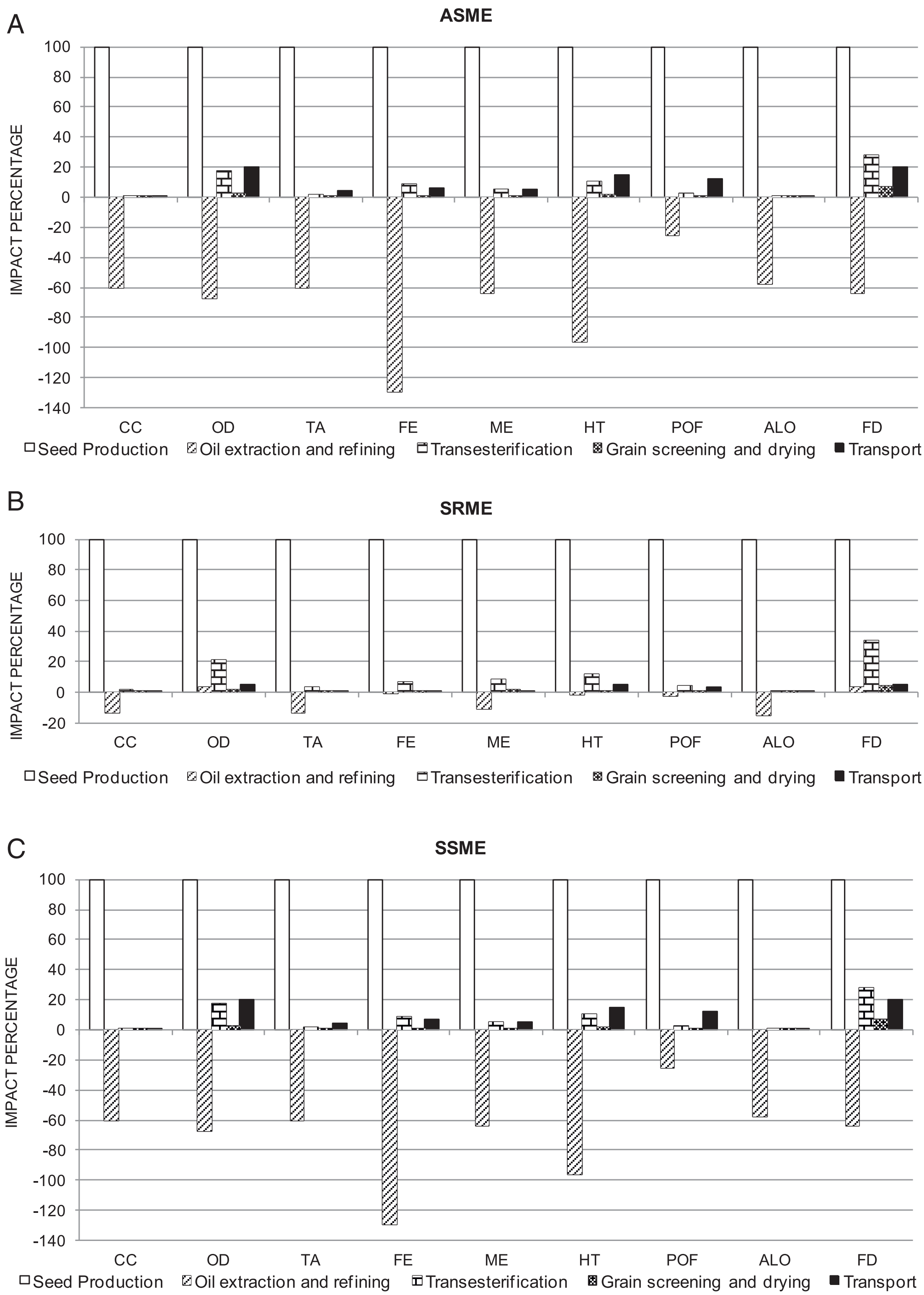

Fig. 5. Relative environmental burdens of the processes of ASME—Argentinean soy methyl ester (A), SRME—Spanish rape methyl ester (B) and SSME—Spanish soy methyl ester (C), according to the ReCiPe Midpoint (H).

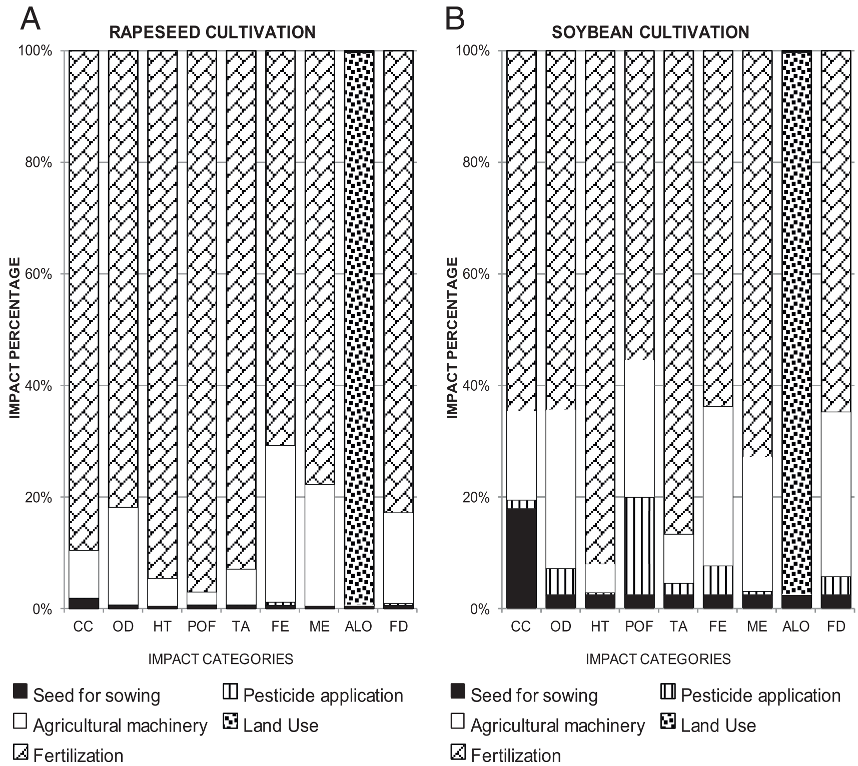

Fig. 6. Relative environmental burdens of 'seed production' sub-processes in Spanish rapeseed production (A) and Argentinean soybean production (B), according to the ReCiPe Midpoint (H) method.

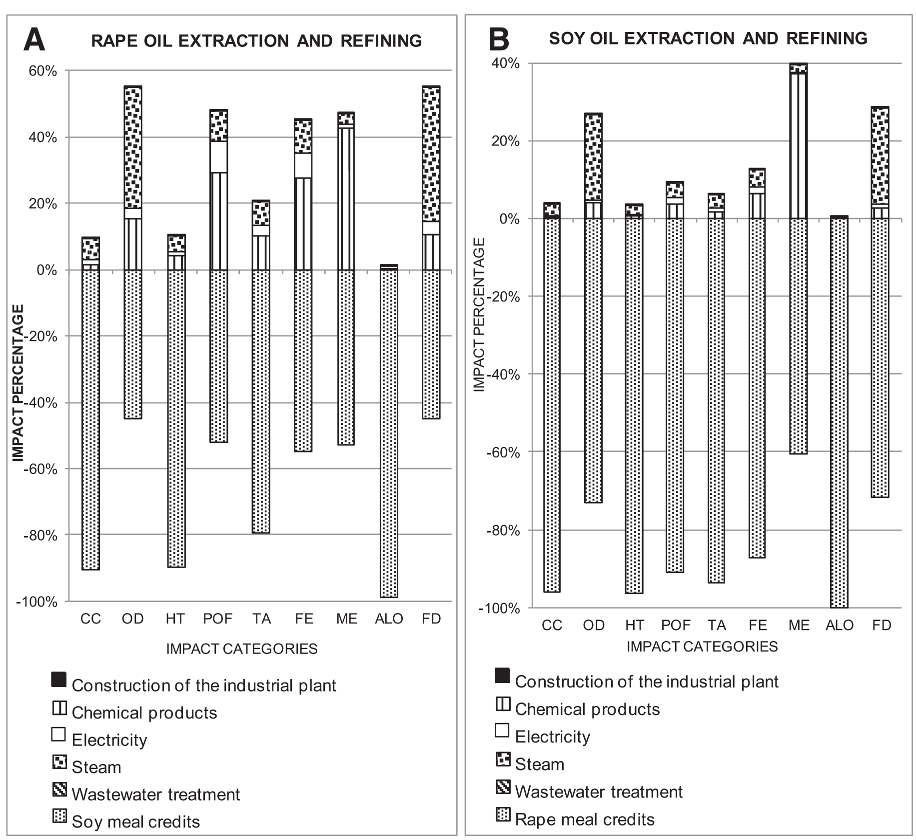

Fig. 7. Relative environmental burdens of the 'oil extraction and refining' sub-processes in Spanish rape oil production (A) and Argentinean soy oil production (B), according to the ReCiPe Midpoint (H) method.

discounted for the press cake in the consequential approach. Therefore, more details are needed for the processes of 'seed production' and 'oil extraction and refining.

Figs. 6 and 7 show the percentage of impact caused (positive values) or avoided (negative values) by every sub-process included in 'seed production', 'oil extraction' and 'oil refining' relative to the total impact in each category. When we focused on 'seed production', we discovered that 'fertilization' is the sub-process with the greatest effect in all the selected impact categories (except in ALO) and is responsible for 56% to 97% of the environmental impacts of both seed production pathways, rapeseed in Spain (Fig. 6a) and soybean in Argentina (Fig. 6b). Within fertilization, nitrogenous fertilization is the main cause of the impacts.

In the ALO category, 'land use' causes higher burdens. 'Agricultural machinery' is the second most critical factor, but its contribution represents less than half of the burdens caused by fertilization in most of the categories addressed.

Within the 'oil extraction and refining' process, it was found that the 'construction of the industrial plant' and 'wastewater treatment' cause insignificant environmental impacts compared with those caused by the use of 'chemical products', 'electricity' and 'steam' (Fig. 7). In rape oil extraction and refining (Fig. 7a), the use of 'chemical products' is the main cause of impacts in the categories POF, TA, FE and ME, while the use of 'steam' in the industrial plant causes the highest burdens in the CC, OD, HT and FD categories. In soy oil extraction and refining (Fig. 7b), the use of 'chemical products' is the main cause of impacts in the categories POF, FE and ME while the use of 'steam' is the main cause of burdens in the categories CC, OD, HT, TA and FD. The use of 'electricity' is responsible for the highest impacts in the ALO category in both systems. The negative values in all categories show the credits discounted for the press cake, which are avoided (in other systems than the one analysed here) when the system is expanded due to the co-products which are produced in the 'oil extraction and refining' process. When rape oil is extracted to produce biodiesel, rape meal is also co-produced. Rape meal can be used to substitute soy meal as animal feed, and therefore soy meal production is avoided in other systems. In the same way, when soy oil is extracted to produce biodiesel, soy

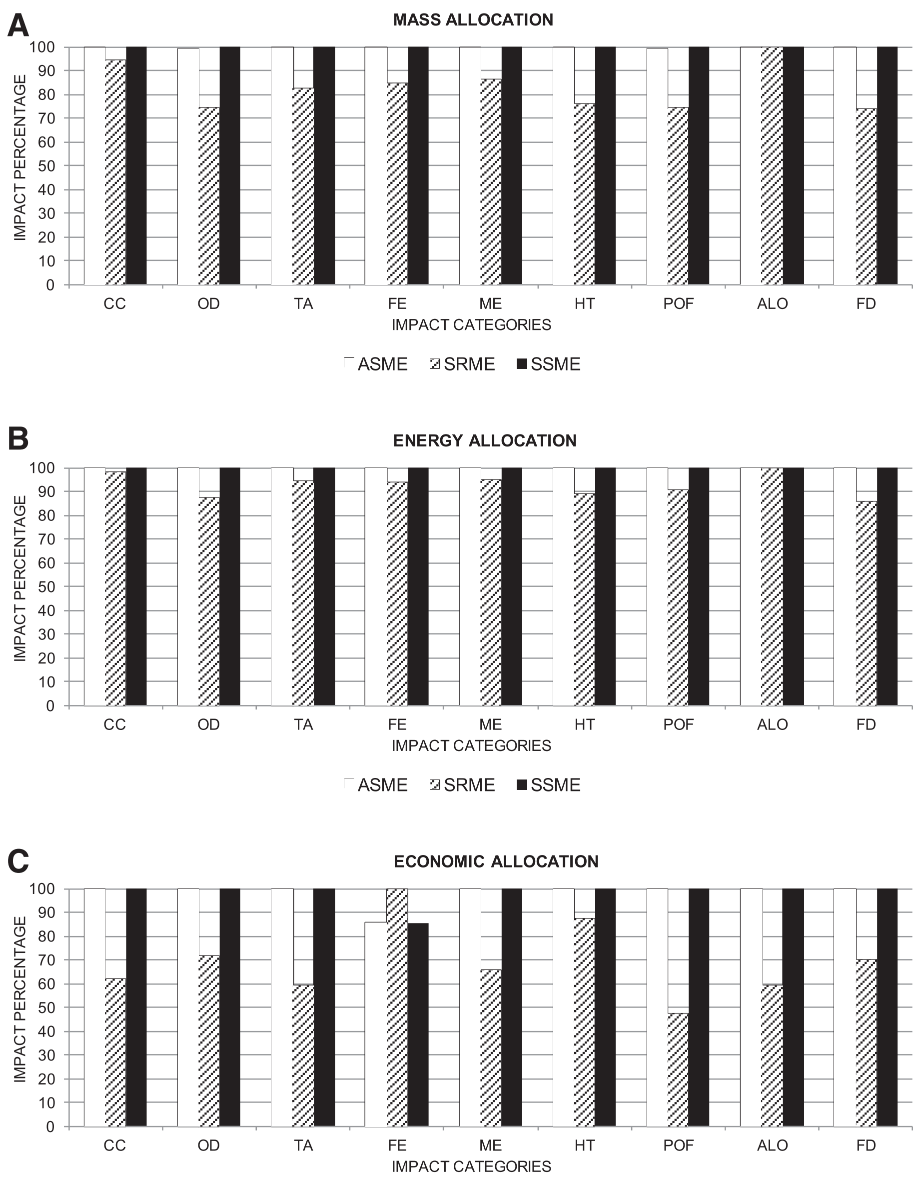

Fig. 8. Environmental impacts of SSME (Spanish soy methyl ester), SRME (Spanish rape methyl ester) and ASME (Argentinean soy methyl ester) according to the ReCiPe Midpoint (H) method and attributional approach.

meal is also co-produced. As soy meal can be used as animal feed to substitute rape meal, the latter is avoided in other systems. Fig. 7 shows that when the same quantity of oil is extracted in both systems (soy and rape) the avoided production of rape meal (Fig. 7b) contributes more positively than the avoided production of soy meal (Fig. 7a).

The sensitivity analysis shows that results are largely dependent on the method used for allocation of the environmental burden between oil and meal in the 'oil extraction and refining' process (Fig. 8). When the attributional approach is used rather than the consequential approach, SRME is the most environmentally friendly pathway, causing fewer impacts in most of the categories addressed, except in FE for the economic allocation approach. Allocation by price attributes to the SRME pathways between 46% and 87% of the burdens caused by the SSME and ASME pathways in most of the impact categories. When allocation by energy content is used, the differences are softened and the impacts caused by SRME are between 86% and 100% of those caused by the other pathways. Physical allocation (mass) attributes to SRME between 74% and 100% of the impacts caused by the other options.

Discussion

The LCA methodology has allowed us to reach conclusions, to select the most sustainable pathway and focus on the processes that could contribute to the development of better management strategies aimed at reducing the impacts in the biodiesel production chain. The analyses carried out in this study highlight that when system expansion is used rather than allocation methods, as ISO 14044:2006 recommends, soybean-based biodiesel produced with feedstock from the Argentinean Pampas has a lower environmental impact than rapeseed-based biodiesel produced with feedstock from the Southwest of Spain.

We agree with Milazzo et al. (2013) on the point that only demonstrably sustainable feedstock should be used in biodiesel production. We also believe that the most sustainable pathway of biodiesel production should be promoted by governments. Consuming soy-based biodiesel instead of rapeseed-based biodiesel would be an efficient solution for improving the sustainability of the Spanish biodiesel consumption. However, in Spain, biofuel policies (MINETUR, 2012a, 2012b, 2014) are leading to an increase in the consumption of rapeseed-based biodiesel and a decrease in soybean-based biodiesel, which is environmentally more sustainable. Seed production is the process that generated the greatest environmental burdens in the LCA of the biodiesel production pathways analysed, especially in rapeseed-based biodiesel production. The strategic role of the agricultural phase on the global impact of biofuels compared to the transport or industrial phases has been noticed in most biodiesel LCAs, for example, CIEMAT (2006); Panichelli et al. (2006); S&T (2010); Fazio and Monti (2011); Requena et al. (2011). When comparing soybean and rapeseed cultivation, it was found that the soy crop required a lower consumption of fertilizers and fewer crop management operations than the rape crop. Therefore, the soybean-based scenarios appeared to be more environmentally efficient than the rapeseed-based scenario. Nitrogen fertilizing is the process that causes the highest impact, so particular attention should be focused on this aspect in Spanish rape crops since rapeseed occupation is expected to continue increasing in Spain (MAGRAMA, 2015a). Our results to some extent contradict the assertions of certain environmental groups (Biofuelwatch, 2012) and authors (Tomei and Upham, 2009) who argue that large-scale biodiesel production, such as Argentinean soybean-based biodiesel, is inherently unsustainable compared to EU domestic production due to its cultivation characteristics, such as pesticide application, N_2O emissions or deforestation. According to our results, from an environmental point of view, soybean has a key advantage over rapeseed in terms of fertilization. Approximately 50% of N removed by the soybean crop is supplied via biological fixation, leading to less need for nitrogen fertilizers, which consequently reduces its environmental impacts (Fernández-Tirado et al., 2013). However, non-leguminous plant species, such as rape, can also fix atmospheric nitrogen when subjected to a process of artificial inoculation of bacteria which form symbiotic relationships with developing plant roots, called paranodules (Koval'skaya et al., 2001). Paranodulation, i.e. the artificial formation of nodules on the roots of non-leguminous plants, would help to reduce the consumption of fertilizers and would be a strategy to reduce the environmental impacts in the rapeseed-based biodiesel chain.

Furthermore, by-products are significant influential factors for the LCA results. Soybean and rapeseed meal are co-produced with soy and rape oil respectively. However, soybean meal wins over rapeseed meal both in quantity produced by tonne of raw material and in selling prices. While 1 t of rape seeds results in 395.6 kg of rape oil and 604.4 kg of rape meal, 1 t of soybeans results in 188.1 kg of soybean oil and 794.0 kg of soybean meal (Jungbluth et al., 2007). In addition, rape meal prices are 36% lower than soy meal prices. Consequently, approximately 65% of the profits of the rape oil extraction industry come from the sale of oil and 35% from the meal. By contrast, 70% of the profits of the soy oil extraction industry come from the sale of meal and 30% from the oil. On this basis, it is essential to consider the meal as a co-product when biodiesel is assessed, as if all the burdens were allocated to the oil, the impacts of soybean-based biodiesel would be a lot higher. In fact, several authors have questioned whether soybean is actually a suitable raw material for biodiesel due to the low oil yield of soybean (Asal et al., 2006; Lamers et al., 2008; Milazzo et al., 2013; Tomei and Upham, 2009) because they did not take into account the meal as a co-product.

Our results also differ greatly from those obtained by Requena et al. (2011), who compared rapeseed-based biodiesel and soybean-based biodiesel without taking co-products into account. In our research, the production of soy meal as a co-product in soybean-based biodiesel is a significant plus to both scenarios, ASME and SSME. Soy meal production avoids rape meal production, in the system expansion method, so the burdens of its production are discounted. As rape cultivation cause higher impacts than soy cultivation, more than half of the burdens which are produced when ASME and SSME systems are analysed without allocation are discounted in all the categories when the system is expanded by including the substitution of rape meal. In particular, in the FE category, rape meal production causes greater P emission into fresh water than soy meal. Higher quantities of triple superphosphate are needed in the Spanish rapeseed production process. By contrast, Argentinean soybean requires less quantity of P as nutrient and consequently less P quantities are emitted into fresh water. Moreover, the quantity of P emission into fresh water subtracted for replacing rape meal exceeded the P emission into fresh water caused by the production of soybean-based biodiesel. Thus the values are negative. By contrast, rape meal is not as valuable (in price terms) as soy meal so fewer credits are discounted when the system is expanded. This brings about the result that Spanish rapeseed-based biodiesel (SRME pathway) has higher environmental impacts than soybean-based biodiesel produced with Argentinean soy oil either in Argentina or in Spain (ASME and SSME pathways). The importance of meal has been cited by other authors, such as Kim and Dale (2005); S&T (2010); Thamsiriroj and Murphy (2010). However, Thamsiriroj and Murphy (2010) reached very different conclusions when the rapeseed-based biodiesel system is expanded with soybean meal avoided, since they used energy allocation instead of economic allocation.

Our results, which are valid for the consequential approach, vary substantially with respect to the attributional approach, due to the patent influence of the allocation method used in this approach. When the three pathways (SSME, SRME, and ASME) are compared using allocation methods (mass, economic or energy) the results are significantly different, as with these methods SRME is the most environmentally sustainable system. We therefore agree with Gonzalez-Garcia et al. (2013) in that the allocation procedure is a critical issue in LCA studies because the environmental results vary considerably according to the allocation factors. We also agree with Bernesson et al. (2004) in that when different biofuels are compared, it is important that the results are calculated with the same allocation strategies and system limitations, since the choice of allocation method may influence the final results considerably.

The results obtained must be interpreted taking into account the assumptions that were made and the limitations of LCA (Reap et al., 2008a, 2008b). We should highlight the aforementioned influence on the results of the choice of methods for the allocation of co-products. However, the strength of LCA lies in the fact that it provides an objective method of calculation, including a holistic and systemic listing of all the inputs and outputs of the system being analysed.

Conclusions

This study permitted the assessment of biodiesel environmental sustainability and the proposal of better management strategies for cleaner production of biodiesel consumed in Spain. The results show that Argentinean soybean is a suitable raw material for biodiesel production. In fact, it is even more environmentally sustainable than the dominant feedstock in EU countries, i.e. rapeseed. These results could contribute to a more efficient design of policies in Spain, since environmental issues are a key driver for the establishment of policies to promote biofuels in the EU.

The greatest environmental impacts are generated in the agricultural phase. Moreover, fertilization is the sub-process which generated the greatest environmental impacts in most of the categories in both seed production systems, i.e. Spanish rapeseed and Argentinean soybean. Since a notable increase of rapeseed-based biodiesel is anticipated in the next few years, improving the fertilization process is a priority, especially for Spanish rape feedstock. Measures focused on reducing the consumption of N fertilizers would lead to a significant decrease in environmental impacts.

Notwithstanding, if the objective of public policy is to promote the sustainable use of biofuels, an analysis of the global sustainability of biodiesel consumed in Spain is needed which includes not only the environmental dimension but also the economic and social dimensions of sustainable development. Hence, it is essential to find out whether the different biodiesel production pathways are generating benefits or disadvantages, such as the creation or loss of jobs, or the stability or expulsion of rural populations, and then to compare Spanish and Argentinean benefits and impacts.

Acknowledgements

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Appendix A. Data sources for the inventory analysis

The data relating to the cultivation of rapeseed were taken from the research project 'RAEA-Biofuels' conducted in IFAPA (Institute of Agricultural and Fisheries Research and Training) from 2006 to 2009. The rapeseed crop was located at the IFAPA Experimental Station in Jerez de la Frontera, in southwest Spain (36°38′N, 06°00′W). Sowing took place in December (2006 and 2007) and in November (2008). The harvest occurred in June (2007 and 2008) and May (2009). The data relating to soybean were taken from the results obtained from the 2009 to 2012 sampling campaigns of the Regional Agricultural Project 'Rural Development' at the Buenos Aires North Regional Centre (CRBAN) located in the INTA Experimental Station in Pergamino, Argentina (33°57′S; 60°32′W). Sowing took place in December (2009) and November (2010 and 2011). The harvest occurred in March in all three years. The harvest date of both rapeseed and soybean depended mainly on grain humidity. Data relating to the biodiesel industry phase of oil refining and transesterification were taken from the literature and compared with the processes used in the two biggest biodiesel plants in Andalusia, located in southwest Spain: Bio-oils Huelva, S.L.U. in the town of Palos de la Frontera in the province of Huelva (37°10′40″N, 6°53′20″W) and Abengoa Bioenergía San Roque, S.A. in the town of San Roque in the province of Cádiz (36°11′23″N, 5°23′22″W). Both industries acquired crude vegetable oil instead of processing seeds. Neither rapeseed nor soybean oil extraction are common in Spain. Therefore, data for screening, drying and oil extraction were taken from the literature.

Appendix B. Information on the use of agricultural machinery

B.1. Inputs

B.1.1. Agricultural machinery in the cultivation of rapeseed in Spain

The farming tasks involved in growing rapeseed were compiled from the Andalusian Network of Agrarian Experiments (RAEA) in biofuels from the Ministry of Agriculture and Fisheries of the Government of Andalusia (IFAPA, 2011a). Data on the agricultural machinery used in Spain was gathered from specific databases such as the agricultural machinery database from the Ministry of Agriculture, Food and Environment (MAGRAMA, 2015b). Table A1 shows the basic characteristics of the machinery used throughout the life cycle of rapeseed cultivation in Andalusia.

Table A1
Farming, characteristics and requirements of agricultural machinery per ha and year for rapeseed production in Andalusia.

Type of machinery	*N*	*W*	*C*	*L*	*F*
Mouldboard plough	1	1000	1.00	3000	21.58
Tillers with flexible arm	2	900	0.25	3000	13.24
Roller	1	300	0.25	800	2.76
Centrifugal fertilizer	2	700	0.04	800	0.74
Seed drill planter	1	810	0.60	1200	7.88
Pesticide sprayer	1	250	0.14	1000	1.02

N: No. of tasks.
W: Weight of the implement (kg).
C: Time required for the task (theoretical capacity to work) (h).
L: Lifetime of the implement (depreciation due to wear)) (h).
F: Fuel consumption (diesel) (l).

In the inventory, the agricultural machinery and the diesel required to perform the work are considered as inputs. The processes for producing the machinery were taken from the Ecoinvent database. The agricultural machinery (*AM*) (in units of mass) needed per functional unit (ha) was calculated according to Eq. (A1):

$$AM = \sum_i W_i C_i / L_i \tag{A1}$$

where i is each tillage implement, W_i the weight of each implement (kg), C_i its theoretical capacity to work (h ha^{-1}), and L_i its lifetime (h).

In addition to the implements, the production process for the tractor needed to perform the farm work was also calculated as an input.

B.1.2. Agricultural machinery in the cultivation of soybean in Argentina

For the first planting of soybeans in the NT system, the tasks required are sowing, pesticide application, fertilization and harvesting (Panichelli et al., 2006). The authors considered that each of these activities must be conducted once during the growing season, except for the application of pesticides, which is performed six times. However, for this analysis, it was considered that pesticide application is performed twice, since this is the current trend. Data regarding each of the aforementioned tasks for one hectare of land are taken from the Ecoinvent database, as shown in Table A2.

Table A2
Tasks carried out per ha and year for soybean production in Pergamino, Argentina.

	No. of tasks
Sowing	1
Pesticide application	2
Fertilization	1
Harvesting	1

B.2. Outputs

In the rapeseed case study, emission factors were used to calculate air emissions, which take the emissions into consideration as a fixed proportion of inputs (Table A3). The emissions of heavy metals into the soil resulting from tyre abrasion were calculated according to Nemecek and Kägi (2007) (Eq. (A2)).

$$HM = \mathrm{Lt}/Lw * Ww/Wt * Cr * Chm * AM \tag{A2}$$

where *HM* are the heavy metals emitted (g ha^{-1}); *Lt* is the lifetime of the tractor (h); *Lw* is the lifetime of the tyres (h), *Ww* is the weight of the tyres (kg), *Wt* is the weight of the tractor (kg); *Cr* is the concentration of rubber in the wheel (dimensionless); *Chm* the concentration of heavy metals in the rubber (dimensionless) and *AM* is the amount of machinery (tractors) needed to perform the work (kg ha^{-1}) obtained according to Eq. (A1). Table A4 shows the values used in this study to apply Eq. (A2).

Table A3
Emissions of gases into the atmosphere of agricultural machinery in the cultivation of rapeseed per kilogramme* of diesel consumed.

Air emission	Emission factor (g Kg^{-1})	Source
Carbon monoxide	2.91E + 01	Audsley et al. (2003)
Carbon dioxide	3.04E + 03	
Nitrogen oxides	5.71E + 01	
Sulphur dioxide	4.15E + 00	
NMVOC	9.16E + 00	
Lead	1.46E-01	Nemecek and Kägi (2007)
Methane	1.29E-01	
Benzene	7.30E-03	
Cadmium	1.00E-05	
Chromium	5.00E-05	
Copper	1.70E-03	
Dinitrogen monoxide	1.20E-01	
Nickel	7.00E-05	
Zn	1.00E-03	
Benzo(a)pyrene	3.00E-05	
Ammonia	2.00E-02	
Selenium	1.00E-05	
Benz(a)-Anthracene	8.00E-05	
Benzo(b) fluor-anthracene	5.00E-05	
Chrysene	5.00E-05	
Dibenzo(a,h)-anthracene	1.00E-05	
Fluoranthene	4.50E-04	

*For a density of 830 kg l^{-1}.

Table A4
Emissions of heavy metals into the soil resulting from tyre abrasion and factors used for its calculation.

	Amount	Unit	Source
Lt	12,000	h	MAGRAMA (2015b)
Lw	2500	–	Nemecek and Kägi (2007)
Ww/Wt	0.0975	–	Nemecek and Kägi (2007)
Cr	0.29	–	Nemecek and Kägi (2007)
CZn	16	g kg^{-1}	Nemecek and Kägi (2007)
CPb	2.6	g kg^{-1}	Nemecek and Kägi (2007)
CCd	0.6	g kg^{-1}	Nemecek and Kägi (2007)
AM	2	h ha^{-1}	MAGRAMA (2015b)
HMZn	2.1786	g ha^{-1}	Equation A2
HMPb	0.3545	g ha^{-1}	Equation A2
HMCd	0.0772	g ha^{-1}	Equation A2

Lt: lifetime of the tractor (h).
Lw: lifetime of the tyres (h).
Ww: weight of the tyres (kg).
Wt: weight of the tractor (kg).
Cr: concentration of rubber in the wheel (dimensionless).
CZn: zinc content in rubber of tyre.
CPb: lead content in rubber of tyre.
CCd: cadmium content in rubber of tyre.
HMZn: Zn emitted (g ha^{-1}).
HMPb: Pb emitted (g ha^{-1}).
HMCd: Cd emitted (g ha^{-1})

Appendix C. Information on the application of pesticides

C.1. Pesticide production

Glyphosate production is inventoried in the Ecoinvent database as a single process, so this active ingredient was selected. However, Trifluraline is not inventoried as such but within the family of compounds of dinitroaniline, so the production process for this family of chemicals was selected.

C.2. Pesticide packaging and waste scenario

Pesticides are usually packaged in HDPE rigid bottles. The weight of these bottles is about 50 g l^{-1}. In both farming systems, a rational management of packaging has been assumed in which farmers comply with the regulations on waste collection and the bottles are then recycled.

C.3. Transport of pesticides

Besides the production process, the transport required to send a pesticide from its place of production to the place where it is applied was also taken into consideration as an input. The rapeseed cultivation takes place in the town of Jerez in the province of Cádiz (Spain) and the soybean crop in the department of Pergamino in the province of Buenos Aires (Argentina). For rapeseed in Jerez, a distance of 500 km, the mean distance of agrochemical transport in Spain (Gasol et al., 2007), was taken. For soybean, 220 km, the distance between Pergamino and the federal capital of Buenos Aires, where the majority of the agrochemical industries are situated, was taken (CIAFA, 2011).

The chosen vehicle is a truck weighing 16 to 32 t, in accordance with Jungbluth et al. (2007). The technology of the selected truck complies with the Euro III standard, since it is the most abundant type of truck in the Spanish fleet (Fomento, 2011). The European standards Euro III, IV and V have also been implemented in Argentina (LCEGV, 2011). In this country, the life span of the trucks is about 14.2 years (UTN, 2007), so the type of truck that complies with Euro III was also chosen.

Appendix D. Literature review of mass and energy use in the industrial processes and data used in this study (per tonne of methyl ester produced).

Table A5
Mass inputs in industrial processes per tonne of RME and SME.

		RME								SME						
		CIEMAT (2006)	Jungbluth et al. (2007)	Halleux et al. (2008)	Esteban et al. (2011)	Dufour et al. (2013)	Gonzalez-Garcia et al. (2013)	Malca et al. (2014)	Data used	CIEMAT (2006)	Panichelli et al. (2006)	Jungbluth et al. (2007)	Donato and Huerga (2009)	Hou et al. (2011)	Castanheira et al. (2015)	Data used
Oil extraction and refining																
Seeds	**kg**	2669	2599		2550	2600	2528	2193	**2523**	5666	5577	5465	5343	5986	5284	**5607**
Phosphoric acid	kg	2.95	0.78				1.01		**1.44**	2.95	0.94				1.36	**2.96**
Citric acid	kg	0.94					0.42		**0.40**	0.94						
Silica gel: Trysil	kg						2.50		**2.05**							**2.05**
Bleaching earth (Bentonite)	kg	12.51	5.98				0.80		**16.16**	12.51					1.20	**16.16**

(continued on next page)

Table A5 (*continued*)

		RME								SME						
		CIEMAT (2006)	Jungbluth et al. (2007)	Halleux et al. (2008)	Esteban et al. (2011)	Dufour et al. (2013)	Gonzalez-Garcia et al. (2013)	Malca et al. (2014)	Data used	CIEMAT (2006)	Panichelli et al. (2006)	Jungbluth et al. (2007)	Donato and Huerga (2009)	Hou et al. (2011)	Castanheira et al. (2015)	Data used
Ammonium nitrate	kg				0.42											
Sodium hydroxide (11.06%)	kg	5.39			5.30		1.91		**13.74**	5.39			0.55		2.28	**23.10**
Cationic resin: Amberlist 15 Dry	kg												3.16			
Hexane	kg	4.69	2.86	2.70	3.06	0.70	2.78	2.19	**2.52**	4.27	11.15	11.48			8.12	**12.12**
Tap water	kg	1042		510	310		161			3060	479	469	1			
Deionized water	g						8.30									
Transesterification and purification																
Oil	**kg**	1023	1028		1020	1080	1020	1020	**1026**	1023	1015	1028	1035	1018	1000	**1026**
Methanol	kg	106	114	109	110	106	98	110	**107**	106	121	114	97	96	105	**107**
Acids	**kg**		4.63									4.63				
Hydrochloric acid	kg	5.20			10.00		13.24		**5.91**	5.20	1.36		3.33		3.07	**5.91**
Sulphuric acid	**kg**						0.30			0.00						
Phosphoric acid	kg	0.04				4.60				0.04	9.53		1.74			
Citric acid	kg						0.28		**9.61**						0.77	**9.61**
Hydroxides	**kg**		11.31									11.31				
Potassium hydroxide	kg							11.00								
Sodium hydroxide	**kg**	1.10					2.35			1.10			4.90		0.44	
Aluminium sulphate	Kg	0.07								0.07						
Ammonium nitrate	Kg	0.71								0.71						
Nitrogen	kg						0.23						3.32			
Potassium methylate	kg						16.70									
Sodium methoxide	kg	4.85							**4.10**	4.85			16.53		5.16	**4.10**
Antioxidant: vitamin D	kg	2.92								2.50			1.89			
Antioxidant: p-Toluenesulfonic acid	kg												0.25			
Silica gel: Trysil	kg												3.06			
Industrial Process water	kg	388	27		390	25	20		**500**	388	27	27	318			**500**
Water consumed by the staff	kg								**12.00**							**12.00**

Table A6
Energy use in industrial processes per tonne of RME and SME.

		RME								SME						
		CIEMAT (2006)	Jungbluth et al. (2007)	Halleux et al. (2008)	Esteban et al. (2011)	Dufour et al. (2013)	Gonzalez-Garcia et al. (2013)	Malca et al. (2014)	Data used	CIEMAT (2006)	Panichelli et al. (2006)	Jungbluth et al. (2007)	Donato and Huerga (2009)	Hou et al. (2011)	Castanheira et al. (2015)	Data used
Grain screening and drying																
Electricity	MJ			119				44	**81**							**81**
Heat (Natural gas)	MJ			812				811	**431**							**1196**
Oil extraction and refining																
Electricity (press)	MJ	2747	370	382	306	90	360		**370**	941	327	1106	596		593	**593**
Electricity (refining)	MJ	92	22	40	90		702		**22**	92					36	**36**
Steam	kg	782	681			430	195		**522**		1980	1475	2044			**1833**
Natural gas (press)	MJ	2908		2317	1826					4634				2688		
Natural gas (refining)	MJ	358		162	357									270		
Heat (fuel oil) (press)	MJ													494		
Transesterification and purification																
Electricity	MJ	59	152	133	60	142	529		**179**	59	148	152	125	144	144	**179**
Steam	kg		342			680	130		**342**		333	342	1232	581		**342**
Natural gas	MJ	1473		947	1440					1473					760	

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