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RESEARCH ARTICLE

Evaluating the environmental sustainability of energy crops: A life cycle assessment of Spanish rapeseed and Argentinean soybean cultivation

Francisca Fernández-Tirado[1,2], Carlos Parra-López[2] and Mercedes Romero-Gámez[3]

[1]*University of Granada. Dept. Civil Engineering. Campus de Fuentenueva s/n. 18071 Granada, Spain.* [2]*Institute of Agricultural and Fisheries Research and Training (IFAPA). Dept. Agri-food Economics. Camino de Purchil s/n. 18004 Granada, Spain.* [3]*Institute of Agricultural and Fisheries Research and Training (IFAPA). Dept. Engineering and Agri-food Technology. Camino de Purchil s/n. 18004 Granada, Spain.*

Abstract

Rapeseed oil is expected to be increasingly used in Spain as raw material to produce biodiesel to the detriment of extra-EU imports of biodiesel mainly based on soybean oil from Argentina. Therefore, the environmental impacts produced throughout the life cycle of energy crops used to produce biodiesel which is consumed in Spain could be radically affected. In this context, the environmental impacts of rapeseed cultivation in Spain and soybean cultivation in Argentina, were compared under certain growing conditions using Life Cycle Assessment (LCA). Two methods of calculation for Life Cycle Impact Assessment (LCIA) and two functional units (FUs) were used to test potential biases. The results showed that the cultivation of soybean in Argentina had, in general, fewer environmental impacts than rapeseed cultivation in Spain when the FU was the area of cultivation, but these findings are inverted when the analysis is conducted according to the energy content of the biodiesel obtained from these crops. Soybean in fact has very low oil content, meaning that larger areas of land are required to obtain the same amount of biodiesel and that consequently it has a higher environmental impact by energy content. Fertilization was, in general, the process that generated the greatest environmental burdens, and is an area in which improvement is necessary in order to increase sustainability, particularly with regard to Spanish rapeseed.

Additional key words: LCA; biodiesel; impacts; CML-IA.

Abbreviations used: ASNPB100kmFF (the amount of seed (kg) needed to produce the biodiesel that would be required to drive 100 km in a diesel Ford Focus 1.8 TDdi 89HP); EU (European Union); FU (functional unit), GHG (greenhouse gas); LCA (life cycle assessment); LCI (life cycle inventory); LCIA (life cycle impact assessment), NT (no till); REOS (respiratory effects of organic substances).

Authors' contributions: Conceived and designed the work; analyzed the data; wrote the paper: FFT. Contributed materials/analysis tools; supervised the work: CPL and MRG. Obtained funding; coordinated the research project: CPL.

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Correspondence should be addressed to Francisca Fernández-Tirado: fernandez@uma.es

Introduction

In recent years, the European Union (EU) has strongly supported the development of biofuels in order to reduce greenhouse gas (GHG) emissions in the transport sector. Different kinds of biofuels can be produced with diverse raw materials and processes, with varying sustainability. Thus the EU is trying to promote second generation biofuels, which are more sustainable. However, the technology is not advanced enough yet, so first generation biofuels will remain in the market in the short or medium term. The European Directive 2009/28/EC on the promotion of the use of energy from renewable sources (EC, 2009), amended by Directive 2015/1513 which established a 7% target for energy from first generation biofuels in transport by 2020 (EC, 2015), restricts public support only to those biofuels and bio-liquids which meet a series of sustainability criteria. In its environmental dimension, it includes requirements for GHG emissions, biodiversity, land use changes and good farming practices. These same criteria were adopted into Spanish law by RD 1597/2011 (BOE, 2011), modified by RD 1085/2015 (BOE, 2015). 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 the brunt of the responsibility for biofuel sustainability is borne by the first stakeholder in the production chain, *i.e.* by farmers. Biofuels produced within or outside the EU, as well as the raw materials used for processing them, must also meet these requirements if they are to be commercialized in the EU market.

The environmental impacts generated by producing first generation biofuel can be very different depending on the raw materials or processes used, even in the case of raw materials that come from the same crop group. Crops such as soybean, rapeseed, palm or sunflower are used to produce biodiesel within the group of oil crops. Since they have very different requirements and management, biodiesel can be produced with different levels of sustainability depending on the crop. As Milazzo *et al*. (2013a) suggest, only demonstrably sustainable feedstock should be used and promoted by governments in biodiesel production. The biodiesel consumed in Spain in 2011 was produced mainly with soybean crops [*Glycine max* (L.) Merr.] from Argentina and palm oil crops (*Elaeis guineensis* Jacq. 1897) from Indonesia (APPA, 2012). However, the Spanish government enacted Order IET/822/2012 (BOE, 2012a), which promotes the production of 4.8 million tonnes of biodiesel in 37 industrial plants located in the EU, 23 of which are in Spain. This has undoubtedly affected the biodiesel market and the sustainability of biodiesel consumed in Spain. It has resulted in a decrease in the consumption of biodiesel from Argentina and an increase in domestic production. In fact, biodiesel demand has already led to a significant expansion of rapeseed (*Brassica napus* L.) oil production in Europe in recent years (Malins, 2013). Rapeseed is the oilseed crop with the highest increase in production over the last decade in Spain (MAGRAMA, 2016)). It is the preferred oil to produce biodiesel because of its quality over other oils (Aldana *et al*., 2012).

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. LCA 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. Thus, LCA has been used to assess environmental burdens caused by agricultural activities, and by the production of energy crops, *i.e.* from a "cradle-to-farm gate" approach. For example, Queirós *et al*. (2015) presented a LCA of rapeseed produced in Central Europe; Mohammadi *et al*. (2013) of soybean in Golestan (province of Iran); and Iriarte *et al*. (2010) of sunflower and rapeseed in Chile. However, most LCA studies on rapeseed crops conducted until now do not delve into the specific conditions of production, such as the cultivation techniques or geographical variability, which is an added value of the present study. A review of these analyses can be found in Malça *et al*. (2014). The same occurs with studies on soybean LCA that have been carried out to date (*e.g*. Kim & Dale, 2009; Panichelli *et al*., 2009; Hou *et al*., 2011; Mohammadi *et al*., 2013). Moreover, most previous studies were limited to energy and GHG emissions, thus excluding other environmental impacts that are relevant throughout the agricultural process.

In this context, the objective of this study was to compare the environmental impacts and sustainability of Argentinean soybean vis-à-vis Spanish rapeseed crops for the production of biofuel, taking into account specific cultivation techniques and geographical variability. That way it is possible to evaluate whether policies that have been recently enacted to support the Spanish biodiesel industry (BOE, 2012a; 2012b) are consistent with the policies on the promotion of the use of biofuels (EC, 2009; 2015; BOE, 2011; 2015) whose main objectives are to reduce GHG emissions and to improve environmental protection, or whether they are in fact having the opposite effect.

Material and methods

Methodology overview

The effects of rapeseed and soybean production on the environment were calculated and evaluated using the LCA methodology. This study uses a 'cradle-to-gate' approach, a partial analysis of the life cycle, from the initial extraction of the raw materials needed to produce the goods and services required for cultivation, through to the harvesting of the seeds. Therefore, in this study, all the input and output flows of materials and energy up to the farm gate were taken into consideration.

In the LCA field it is increasingly being advocated that hectare per year should be used as the functional unit for biofuel analysis in parallel with energy content (MJ fuel and if possible transport service per km). The hectare as a functional unit (FU) is useful to reflect the area efficiency and is expected to become more important in the future given the increasing competition of cropland for food, animal feed, energy, etc (Börjesson *et al*., 2010). Therefore, two FUs were used in this study: One hectare of crop, and the amount of seed (kg) needed to produce the biodiesel that would be required to drive 100 km in a diesel Ford Focus 1.8 TDdi 89HP (ASNPB100kmFF). This is a vehicle that is representative of the Spanish fleet that consumes biodiesel in the scope of this study. Both FUs allowed us to compare the environmental impacts and sustainability of agriculture both in terms of land as a production factor and in terms of the energy obtained from the crops.

To cover the data requirements for the inventory analysis, different data sources were used to obtain representative production data. The data relating to the cultivation of rapeseed were taken from the research project 'RAEA-Biofuels' conducted in IFAPA (Andalucía, Spain) from 2006 to 2009. The rapeseed crop was located at the IFAPA Experimental Station in Jerez de la Frontera (Cádiz, Spain) (36º 38' N, 06º 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 2009-2012 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. The data used could be considered a good estimate not only at local level, but also at country level, since the yields obtained in the trials do not differ greatly from the national averages. Also, cultivation techniques, equipment and infrastructures used in the trials are commonly used at national level in both crops. The software 'Simapro 7.3.2' developed by PRe' Consultants and the database 'Ecoinvent v2.2' (Ecoinvent, 2010) were used for the environmental assessment, taking into consideration the classification and characterization phases set out in ISO14040 (2006) and ISO14044 (2006), a standard which specifies the general framework, principles and basic requirements for conducting LCA studies. When the processes from Ecoinvent v2.2 did not fit for the areas from this study, for example, due to climatic, edaphological or technological differences, specific processes were executed.

To test potential methodological biases, two methods of calculation were used: CML-IA and Eco-indicator 99 for life cycle impact assessment.

The PestLCI model developed by Birkved & Hauschild (2006) was used to calculate pesticide emissions. This model quantifies the proportions emitted to the atmosphere, surface water and groundwater. The PestLCI model was implemented on an Excel spreadsheet and includes a database with the physical and chemical properties of 69 pesticides and the different types of application (incorporation into the soil, spray, etc.). The model parameters relate to crop type and stage of development, as well as to agronomic and climatic variables. Climate and soil data were taken from Monge *et al*. (2008) and IFAPA (2011a) for the rapeseed crop in Jerez and from INTA (2002; 2013) for the soybean crop in Pergamino.

Life cycle inventory (LCI)

This phase involves the collection and quantification of inputs and outputs of matter and energy for all processes that are involved throughout the life cycle

Table 1. Farming, characteristics and requirements of agricultural machinery per hectare and year for rapeseed production in Andalusia.

Type of machinery	N	W	C	L	F
Mouldboard plough	1	1,000	1.00	3,000	21.58
Tillers with flexible arm	2	900	0.25	3,000	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	1,200	7.88
Pesticide sprayer	1	250	0.14	1,000	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). *Source:* Data from MAGRAMA (2014).

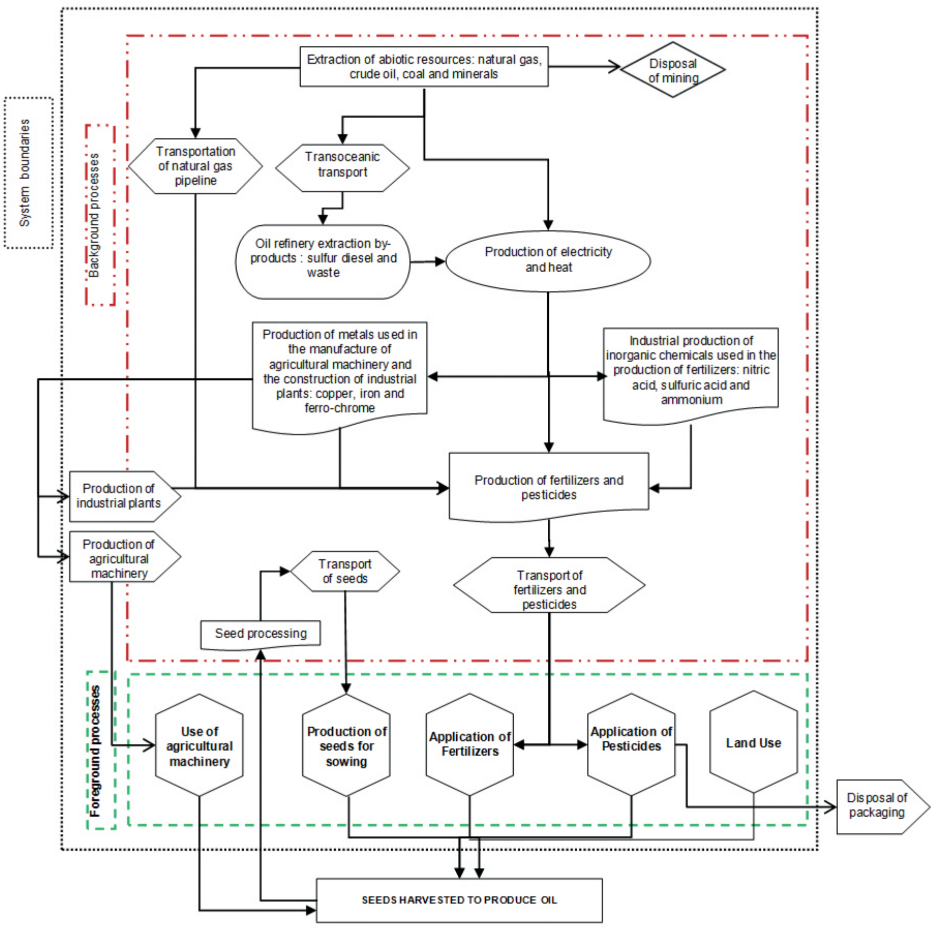


Figure 1. Diagram of the seed production system boundary.

of a product, which in our case studies are rapeseed and soybean. The inputs/outputs and the procedures used for each of the two cropping systems analysed are detailed below. Fig. 1 shows a general flow diagram for the two production systems considered, which were structured in several stages for the inventory analysis, each one including processes and flows, in order to facilitate the study and interpretation of the results: use of farm machinery for agricultural work, application of pesticides, application of fertilizers and production of seeds for sowing.

Use of farm machinery for agricultural work

a) *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 Council of Agriculture and Fisheries of the Regional Government of Andalusia (IFAPA, 2011b). 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, 2014). Table 1 shows the basic characteristics of the machinery used throughout the life cycle of rapeseed cultivation in Andalusia.

The production process for the tractor needed to perform the farm work was also calculated as an input. 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. Emission factors were used to calculate air emissions, which take the emissions into consideration as a fixed proportion of inputs (Table 2). The emissions of heavy metals into the soil resulting from tyre abrasion (HM) were calculated according to Nemecek & Kägi (2007) by applying equation [1]: (HM = Lt/Lw * Ww/Wt * CR *Chm * AM). The results and the coefficient needed for its calculations are shown in Table 3.

b) *Agricultural machinery in the cultivation of soybean in Argentina*

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. Currently, about 67%

Table 2. Emissions of gases into the atmosphere of agricultural machinery in the cultivation of rapeseed per kilogram[1] of diesel consumed.

Air emission	Emission factor (g/kg)	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 & 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	

[1]For a density of 830 kg/L

Table 3. 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 (2014)
Lw	2,500	-	Nemecek & Kägi (2007)
Ww/Wt	0.0975	-	Nemecek & Kägi (2007)
CR	0.29	-	Nemecek & Kägi (2007)
CZn	16	g/kg	Nemecek & Kägi (2007)
CPb	2.6	g/kg	Nemecek & Kägi (2007)
CCd	0.6	g/kg	Nemecek & Kägi (2007)
AM	2	kg/ha	MAGRAMA (2014)
HMZn	2.1786	g/ha	Equation [1]
HMPb	0.3545	g/ha	Equation [1]
HMCd	0.0772	g/ha	Equation [1]

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 (g/kg). CPb: Lead content in rubber of tyre (g/kg). CCd: Cadmium content in rubber of tyre (g/kg). AM: Amount of machinery (tractors) needed to perform the work (kg/ha). HMZn: Zn emitted (g/ha). HMPb: Pb emitted (g/ha). HMCd: Cd emitted (g/ha).

Table 4. Bibliographic sources used for calculating the input and output from pesticides.

	Spain	Argentina
Production	Glyphosate (Nemecek & Kägi, 2007)	Dinitroaniline (Nemecek &Kägi, 2007)
Packaging	50 g/L high-density polyethylene rigid bottles (Ecoembes, 2013)	50 g/L high-density polyethylene rigid bottles (Ecoembes, 2013)
	500 km (Gasol et al., 2007) in 16-32 tons truck (Jungbluth *et al*., 2007) which complies with Euro III standard (Fomento, 2011)	220 km (CIAFA, 2011) in 16-32 tons truck (Jungbluth *et al*., 2007) which complies with Euro III standard (UTN, 2007)

of first planting soybeans and 100% of second planting soybeans are cultivated by NT (Asal *et al*., 2006).

The farm work and agricultural machinery required per FU were taken from Panicheli *et al*. (2006). For the first planting of soybeans in the NT system, the tasks required are sowing, pesticide application, fertilization and harvesting (Panicheli *et al*., 2006). These 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, according to research conducted for glyphosate in the Pampas (INTA, 2010). Data regarding each of the aforementioned tasks for 1-ha of land are taken from the Ecoinvent v2.2 database.

Application of pesticides

In the rapeseed crop trials carried out in Jerez, 1.5 L/ha of the pesticide TREFLAN, whose active ingredient is Trifluraline at a concentration of 480 g/L, were applied (IFAPA, 2011b), *i.e.* 720 g/ha were needed. Such treatment was 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 480 g/L. According to the manufacturers of this type of herbicide, in large soybean extensions, two applications with an average dose of 22.5 L/ha in each application (mixing glyphosate with water at 10% concentration), are needed once the crop has emerged, *i.e.* 2160 g/ha were needed. The main form of application is spraying from aircraft over large areas of land (SADSA, 2008). The production of pesticides and their transport to the application site were incorporated as inputs for both crops in the inventory of pesticides. The procedures for calculating these inputs are summarized in Table 4. Pollutant emissions into air and water were taken into consideration as outputs.

Table 5 shows the emission of active substances of the pesticides into the different areas of the environment, which were calculated with PestLCI model developed by Birkved & Hauschild (2006) and inserted in Simapro.

Fertilizers application

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 input and outputs of fertilization were taken from the LCI of Fernández-Tirado *et al*. (2013). Moreover, the packaging of fertilizers in 50 kg low-density polyethylene 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 abovementioned production process of seed cultivation itself was included in our calculations. To grow 1-ha of rapeseed, 7 kg of seeds are needed (IFAPA, 2011b) while 75 kg are needed to grow 1-ha of soybean (Panichelli *et al*., 2006). Secondly, the transport needed to bring the seeds from the field to the processing 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). This is due to the fact that soybean farmers require more seeds per hectare, as indicated above, and 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 Nemecek & Kägi (2007) and Jungbluth *et al*. (2007). Finally, the energy used to process the seed was calculated in the same way as in Gasol *et al*. (2007), *i.e.* 58 kWh/t of seed.

Life Cycle Impact Assessment (LCIA)

The CML-IA methodology was used to quantify the impacts in the LCIA phase (Guinée *et al*., 2002). According to ISO14044 (2006), this phase includes three mandatory elements: selection of impact categories, classification and characterization (Table 6).

Table 5. Pesticide emission fraction in the analysed case studies (g/kg).

	Trifluralin 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 which is emitted to the air. FSW: fraction of pesticide released to surface waters. FGW: fraction of pesticide emitted to groundwater.

In the CML-IA method the classification is performed in parallel with the characterization process.

Sensitivity analysis

The sensitivity analysis is an optional element of LCA to estimate the validity of the results of the LCIA. As different cultivation techniques are possible in both crops, different scenarios with variations in the inputs/outputs are used to compare the results with the baseline scenario (rape baseline and soy baseline). The comparison of the different scenarios allows us to identify the alternatives that could best contribute to reducing the impacts and achieving better management strategies. Yields of 2800 kg/ha for the rapeseed scenarios and 3320 kg/ha for the soy scenarios were assumed, similar to the baseline scenarios. The new scenarios for the calculation of the impacts are as follows:

- Rape Norest scenario: it is assumed that the crop residues are not left in the soil.
- Rape NT scenario: a no till system, *i.e.* a tillage system with minimum ploughing work is assumed, in which the primary and secondary tillage of the soil are excluded.
- Soy 3Pest scenario: This assumes that triple the amount of pesticide is used. Thus six pesticide applications instead of two are carried out, in accordance with Panichelli *et al*. (2006).

Additionally, as a sensitivity analysis, the characterised results were compared with other methods of calculation: The Eco-indicator 99 (H), in the hierarchist perspective (Goedkoop & Spriensma, 2001), was used instead of the CML-IA method, using both FUs. Although these methods differ in their proposed impact categories, generally they address the same environmental issues. In this way, the effects of the method chosen on the results can be assessed, and the robustness of the study can be verified when the results obtained by different methods are similar. Moreover, a damage assessment, which combines a number of impact category indicators into a damage category, was performed with the Eco-indicator 99 (H) method. In this methodology, the environmental impacts are related to three damage categories: human health, ecosystem qulity and resources depletion.

Results

Results obtained using the CML-IA method

Environmental impacts using 1-ha/yr as the functional unit

The rapeseed crop in Spain in any scenario (Rape baseline, Rape Norest and Rape NT) caused higher environmental impacts than the soybean crop in Argentina in any scenario (Soy baseline and Soy 3Pest). This occurred in all the selected impact categories (Fig. 2a). The Soy baseline scenario was the most environmentally friendly since its burdens represented 50% to 72% of the most critical scenarios (Rape baseline and Rape Norest).

Environmental impacts using ASNPB100kmFF as the functional unit

When energy content was chosen as the FU, the opposite results were obtained. Hence, both soybean production scenarios in Argentina caused higher impacts than the rapeseed production scenarios in Spain in all the selected impact categories. The Soy 3Pest scenario resulted the worst for the environment (Fig. 2b). The rape crop scenarios caused 55% to 89% of the impacts caused by the Soy3Pest scenario.

Effect of every process in the impact categories

In methodological terms, the impact of each process in the selected impact categories does not depend on the FU (1-ha/yr or ASNPB100kmFF). This was calculated for the three rapeseed scenarios (Fig. 3) and the two soybean scenarios (Fig. 4). Fertilization is the process with the greatest effect in all the selected impact categories for all the scenarios, both in the cultivation of rapeseed in Spain (Fig. 3) and soybean in Argentina (Fig. 4). Agricultural machinery is the second most harmful process, especially in the case of soybean in Argentina for the HT (human toxicity), OLD (ozone layer depletion) and AD (abiotic resource depletion) categories.

Table 6. Selection of impact categories, life cycle inventory (LCI) results, characterization models, category indicators, characterization models and measurement units in each impact category.

Impact categories	LCI results	Characterization models	Category indicators	Characterization factors	Category indicator unit
Depletion of abiotic resources (AD)	Extraction of mineral and fossil fuel	Approach based on the concentrations of reserves and extraction rate	Depletion of resource related to annual consumption	Potential depletion of resources for each mineral and fossil fuel extracted	kg Sbeq
Acidification (Ac)	Air emissions of acidifying substances	RAINS10 Model developed by IIASA[1]	Critical loads of acidification on ecosystems	Potential of acidification for each acidifying air emission	kg SO_2eq
Eutrophication (Eu)	Nutrient emissions to air, water and soil	Stoichiometric procedure which relates biomass formation with emissions of nutrients and BOD	Biomass production in relation to [N] and [P] and BOD in the water	Eutrophication potential of each substance emitted to air, water or soil	kg PO_4eq
Global warming (GW)	GHG emissions to air	IPCC[2] model that defines the global warming potential of greenhouse gases	Infrared radiative forcing (W/m^2)	Global warming potential (GWP100) for each GHG	kg CO_2eq
Ozone layer depletion (OLP)	Air emissions of gases that cause stratospheric ozone to break down	WMO[3] model that defines the ozone depletion potential of different gases	Stratospheric ozone breaking down	Potential for breaking down the stratospheric ozone in steady state for each substance emitted to air	kg CFC-11eq
Human toxicity (HT)	Toxic substance emissionsinto air, water and soil	USES 2.0 model developed by RIVM[4], describing fate, exposure and effects of toxic substances	Acceptable daily intake (ADI)	Human toxicity potential of each toxic substance emitted to air, water or soil	kg 1,4 $C_6H_4C_{12}$eq
Photochemical oxidation (PO)	Air emissions of VOC-CO substances	Trajectory model developed by the UNECE[5]	Tropospheric ozone formation	Potential of photochemical ozone formation for each VOC and CO emission to air	kg C_2H_4eq

[1] International Institute for Applied Systems Analysis (Laxenburg, Austria). [2] Intergovernmental Panel on Climate Change (Geneva, Switzerland). [3] World Meteorological Organization (Geneva, Switzerland). [4] National Institute for Public Health and the Environment (Bilthoven, The Netherlands). [5] United Nations Economic Commission for Europe (Geneva, Switzerland). BOD, biochemical oxygen demand. GHG, greenhouse gas. VOC-CO, volatile organic compounds and carbon monoxide.

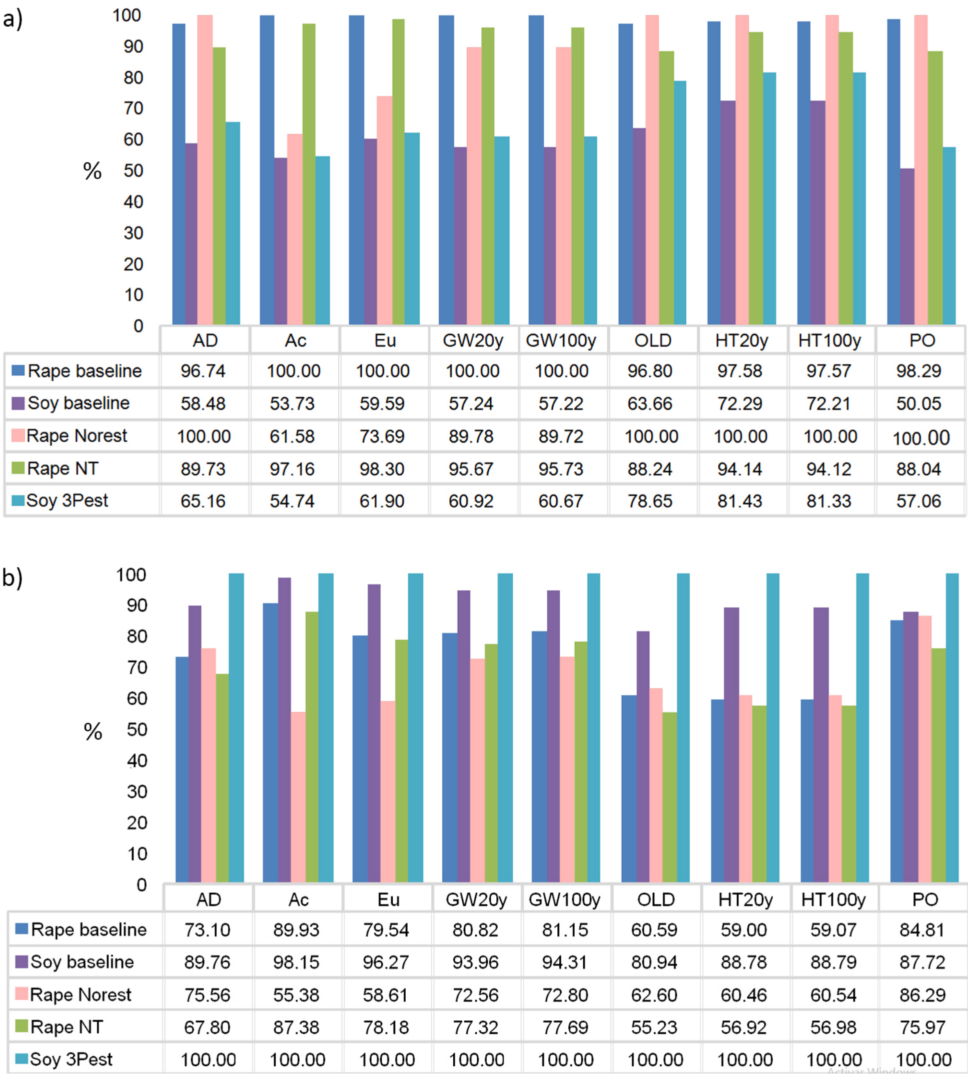
Results obtained using the Eco-indicator 99 method

Environmental impacts using 1-ha/yr as the functional unit

The results obtained using the alternative Eco-indicator 99 method confirmed that the environmental impacts generated by the cultivation of 1-ha of rapeseed in Spain are greater than those generated by the cultivation of 1-ha of soybean in Argentina for the baseline scenarios (Fig. 5a). However, some rapeseed crop scenarios produce fewer environmental impacts than either of the soybean scenarios in certain impact categories. Specifically, Rape NT has a lower impact than the two soy scenarios (Soy baseline and Soy 3Pest) in the respiratory effects of organic substances (REOS) category. Moreover, Rape Norest generated the lowest environmental burdens when compared to the two soy scenarios in the respiratory effects of inorganic substances (REIS) and Acidification/Eutrophication categories.

Environmental impacts using ASNPB100kmFF as the functional unit

The results were very different if the energy content was taken as the FU (Fig. 5b). The environmental impacts



a)

	AD	Ac	Eu	GW20y	GW100y	OLD	HT20y	HT100y	PO
Rape baseline	96.74	100.00	100.00	100.00	100.00	96.80	97.58	97.57	98.29
Soy baseline	58.48	53.73	59.59	57.24	57.22	63.66	72.29	72.21	50.05
Rape Norest	100.00	61.58	73.69	89.78	89.72	100.00	100.00	100.00	100.00
Rape NT	89.73	97.16	98.30	95.67	95.73	88.24	94.14	94.12	88.04
Soy 3Pest	65.16	54.74	61.90	60.92	60.67	78.65	81.43	81.33	57.06

b)

	AD	Ac	Eu	GW20y	GW100y	OLD	HT20y	HT100y	PO
Rape baseline	73.10	89.93	79.54	80.82	81.15	60.59	59.00	59.07	84.81
Soy baseline	89.76	98.15	96.27	93.96	94.31	80.94	88.78	88.79	87.72
Rape Norest	75.56	55.38	58.61	72.56	72.80	62.60	60.46	60.54	86.29
Rape NT	67.80	87.38	78.18	77.32	77.69	55.23	56.92	56.98	75.97
Soy 3Pest	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Figure 2. Environmental impacts of rapeseed cultivation in Spain and soybean cultivation in Argentina for the different proposed scenarios according to the CML-IA method. a: Functional unit: 1 ha/yr of crop. b: Functional unit: ASNPB100kmFF. AD: abiotic resource depletion; Ac: acidification; Eu: eutrophication; GW: global warming (in 20 and 100 years); OLD: ozone layer depletion; HT: human toxicity (in 20 and 100 years); PO: photochemical oxidation. Rape Norest: no crop residues; Rape NT: no tillage; Soy 3Pest: triple amount of pesticides.

were greater for the Argentinean soybean scenarios in all the impact categories, except for carcinogens.

Effect of every process in the impact categories

Fertilization was the process with the highest environmental burden for all the impact categories in all the scenarios when the Eco-indicator 99 was used (Figs. 6 and 7). Agricultural machinery was the second most harmful process, especially for soy in Argentina due to its influence on the REOS, mineral and ozone layer categories.

Damage analysis using both 1-ha/yr and ASNPB100kmFF as the functional units

The damage analysis carried out using the Eco-indicator 99 method and using 1-ha/yr as the FU (Fig. 8a) shows that the rapeseed baseline scenario caused the highest impacts in two of the damage categories (human health and ecosystem quality) whereas the rape with no crop residues (Norest) scenario causes the highest impact in the resources damage category. By contrast, the rape with no crop residues (Norest) scenario caused the lowest impact in the human health and ecosystem quality damage categories whereas the soy baseline scenario caused the lowest impact in the resources damage category.

The results of the damage assessment (Fig. 8b) show that the rape baseline scenario caused the lowest impacts in the three damage categories (human health, ecosystem quality and resources) if energy content was taken as the FU, whereas the soy cultivation using triple the amount of pesticides (Soy 3Pest) scenario caused the highest impacts.

In any case, the results were in concurrence with those of the rest of the analysis: rape had higher impacts

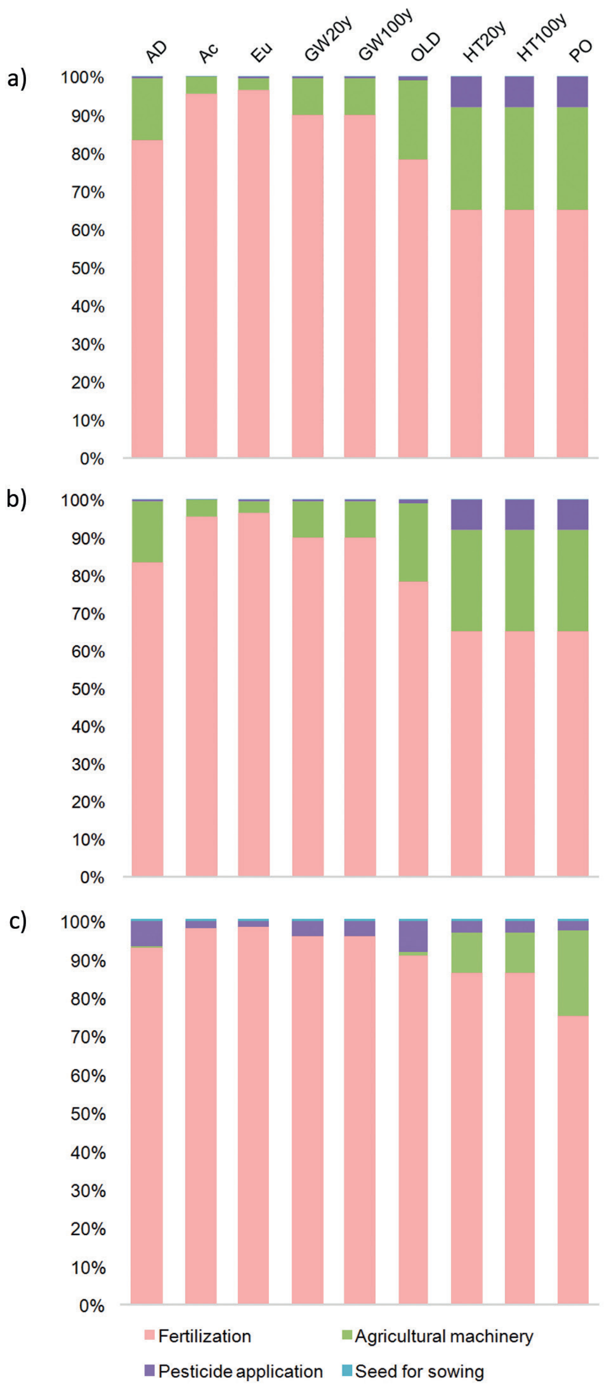


Figure 3. Environmental burdens of the processes involved in the cultivation of rapeseed in Spain according to the CML-IA method. a: Rape baseline scenario; b: Rape Norest scenario; c: Rape NT scenario.

than soy when surface area was used as the FU, whereas the opposite was true when energy content was used.

Discussion

The analyses carried out in this study highlight that when 1 ha/yr was chosen as the FU, soybean cultivation

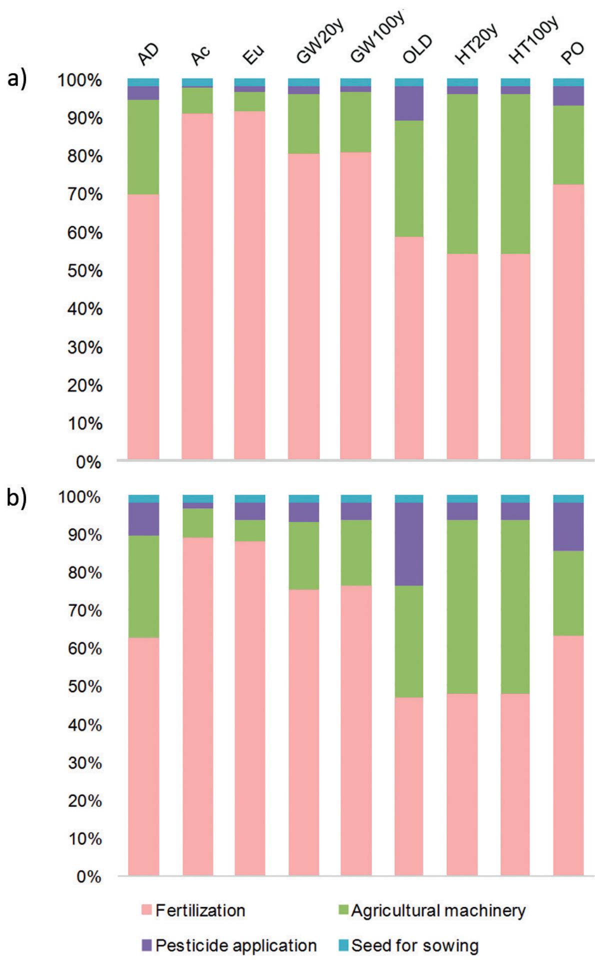
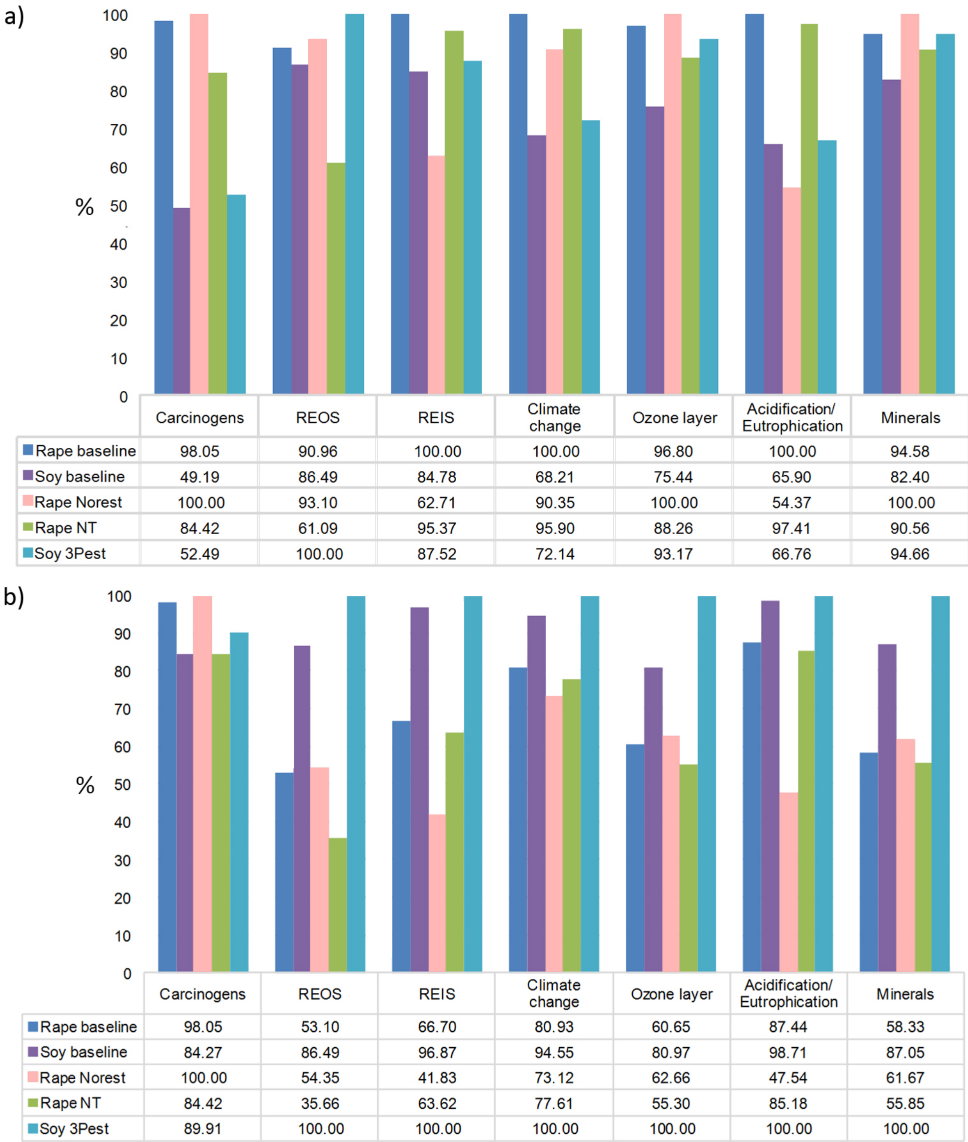


Figure 4. Environmental effects of the processes involved in the cultivation of soybean in Argentina according to the CML-IA method. a: Soy baseline scenario; b: Soy 3Pest scenario.

had a lower environmental impact than rapeseed cultivation. These results to some extent contradict the assertions of some environmental groups who argue that large-scale agricultural production, such as soybean in Argentina, is inherently unsustainable compared to EU domestic production (Biofuelwatch, 2007). However, these results, which are valid for the baseline scenarios, must be qualified when comparing other specific scenarios, taking the patent influence of the method of calculation into consideration. When both crops were compared based on energy content as the FU, the results varied significantly. The soybean crop in Argentina then caused higher impacts in general. The effect of the FU can be explained by the fact that the soybean has an oil content lower than rapeseed, meaning that large areas of land are required to obtain the same amount of biodiesel, and that more environmental impacts are generated. Therefore, several authors have questioned whether soybean is actually a suitable raw material for biodiesel (Asal *et*



a)

	Carcinogens	REOS	REIS	Climate change	Ozone layer	Acidification/ Eutrophication	Minerals
Rape baseline	98.05	90.96	100.00	100.00	96.80	100.00	94.58
Soy baseline	49.19	86.49	84.78	68.21	75.44	65.90	82.40
Rape Norest	100.00	93.10	62.71	90.35	100.00	54.37	100.00
Rape NT	84.42	61.09	95.37	95.90	88.26	97.41	90.56
Soy 3Pest	52.49	100.00	87.52	72.14	93.17	66.76	94.66

b)

	Carcinogens	REOS	REIS	Climate change	Ozone layer	Acidification/ Eutrophication	Minerals
Rape baseline	98.05	53.10	66.70	80.93	60.65	87.44	58.33
Soy baseline	84.27	86.49	96.87	94.55	80.97	98.71	87.05
Rape Norest	100.00	54.35	41.83	73.12	62.66	47.54	61.67
Rape NT	84.42	35.66	63.62	77.61	55.30	85.18	55.85
Soy 3Pest	89.91	100.00	100.00	100.00	100.00	100.00	100.00

Figure 5. Environmental impacts of rapeseed in Spain and soybean in Argentina for the different proposed scenarios according to the Eco-indicator 99 (H) method. a: Functional unit: 1 ha/yr of crop. b: Functional unit: ASNPB100kmFF

al., 2006; Lamers *et al*., 2008; Tomei & Upham, 2009; Milazzo *et al*., 2013b). It is also necessary to take into account the risk of displacement of other crops, which is higher for soybean compared to rapeseed, which could pose a threat to biodiversity, climate change and food security. With this in mind, according to BOE (2009), the Commission should monitor the impacts of biofuels including impact as a result of indirect land-use change. Fertilization is the process that generated the greatest environmental burdens in all the scenarios for both crops, but especially rapeseed. Due to methodological rationale, the FU did not influence these burdens. Fertilization was the most significant factor in most of the categories (Fig. 3) for both case studies, mainly due to nitrate emissions into the air and water. Nitrates were responsible for the greatest environmental impacts, and therefore it can be concluded from the results that it is a priority to improve the fertilization process, especially for rape. From an environmental point of view, soybean has a key advantage over rapeseed. Approximately 50% of N removed by the soybean crop is supplied via biological fixation, leading to less need for nitrogen fertilizers, consequently reducing the environmental impacts (Fernández-Tirado *et al*., 2013). Non-leguminous plant species, such as rape, might be able to fix atmospheric nitrogen following a process of artificial inoculation of bacteria which form symbiotic relationships with developing plant roots, called paranodules. Paranodulation would help to reduce the consumption of inorganic nitrogen and would bring major environmental benefits to the rapeseed crop in Spain (Fernández-Tirado *et al*., 2013).

Figure 6. Environmental effects of the processes involved in the cultivation of rapeseed in Spain according to the Eco-indicator 99 (H) method. a: Rape baseline scenario; b: Rape Norest scenario; c: Rape NT scenario.

The results obtained must be interpreted taking into account the assumptions that were made and the limitations of LCA (Reap *et al.*, 2008a,b). We should highlight the aforementioned influence on the results of the choice of FU and method of calculation, the difficulties in the selection of the system boundaries, the exclusion of social and economic aspects, and the various methods for calculating the impact allocation of co-products. We could also cite some weaknesses of this study, such as the influence on the overall results of other assumptions than those included in the sensitivity analysis, the use of average data without considering associated variability, the quality of some emission factors considered in the calculations, the scope of the study being a "cradle-to-farm gate" approach, *i.e.*, just the agricultural phase of the biodiesel LCA, or the limitation of the results to a determined production context in Pergamino, in the Argentinean Pampas, and in Jerez, in the south of Spain. However, the final results of the study can be extrapolated to other regions with similar soil and climate conditions. On the positive side, 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.

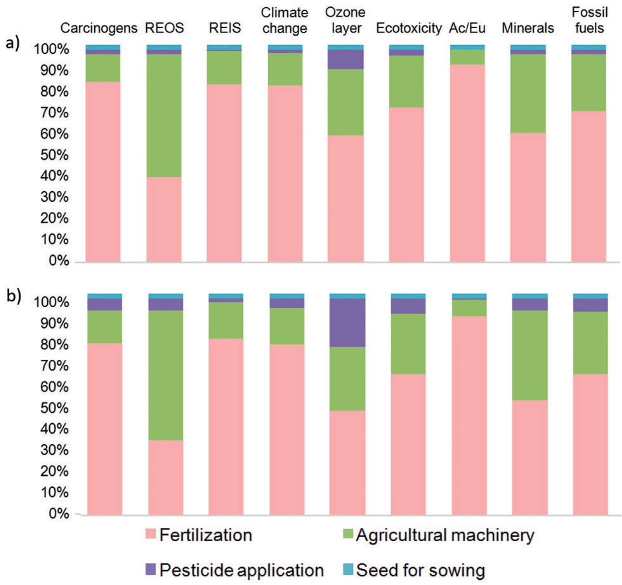


Figure 7. Environmental impact of the processes involved in the cultivation of soybean in Argentina according to the Eco-indicator 99 (H) method. a: Soy baseline scenario; b: Soy 3Pest scenario.

The LCA methodology has allowed us to reach conclusions, to define limitations and to identify crops and cultivation techniques that could contribute to reducing the impacts of biodiesel consumed in Spain. Although Spanish rapeseed and Argentinean soybean are grown in very different contexts, both can be used to produce biodiesel consumed in Spain. This study permitted the assessment and proposal of better management strategies for cleaner production

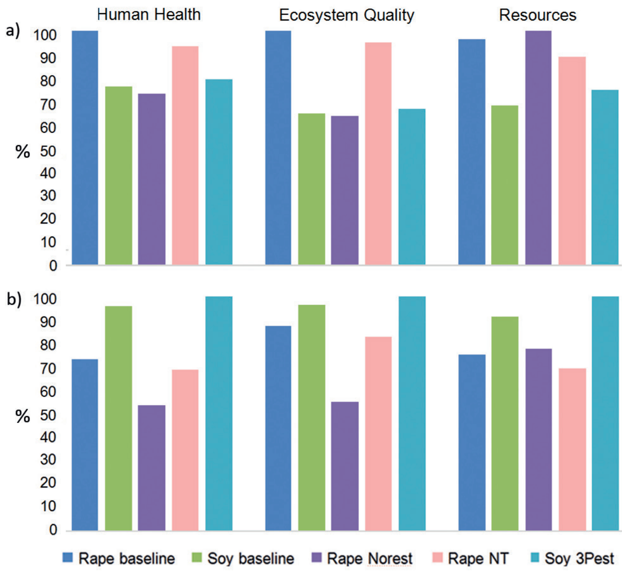


Figure 8. Damage assessment of rapeseed and soybean for the different proposed scenarios according to the Eco-indicator 99 (H) method. a: Damage assessment with 1-ha/yr as the functional unit; b: Damage assessment with the ASNPB100kmFF as the functional unit.

of Spanish rapeseed and Argentinean soybean. The results obtained using the LCA for the specific local cultivation techniques and geographical conditions demonstrate that fertilization was the process that generated the greatest environmental impacts for both crops. Measures focused on reducing the consumption of mineral fertilizers would lead to a significant decrease in environmental impacts. Leguminous species such as soybean are more environmentally sustainable than non-leguminous species, such as rapeseed since leguminous species improve the soil, require fewer inputs and release fewer outputs to the environment.

The effect of the recent Spanish regulations that affect energy crops, which could encourage farmers to cultivate rapeseed, is not clear and should be further investigated. A complete life cycle of biodiesel (*i.e.*, a well-to-wheel LCA of biodiesel), including transport and consumption of biodiesel, should be evaluated in future research in order to complete the environmental impact picture. Moreover, an analysis of global sustainability of energy crops which includes not only the environmental dimension but also the economic and social dimensions of sustainable development, is needed. Hence, it is essential to find out whether these crops 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.

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